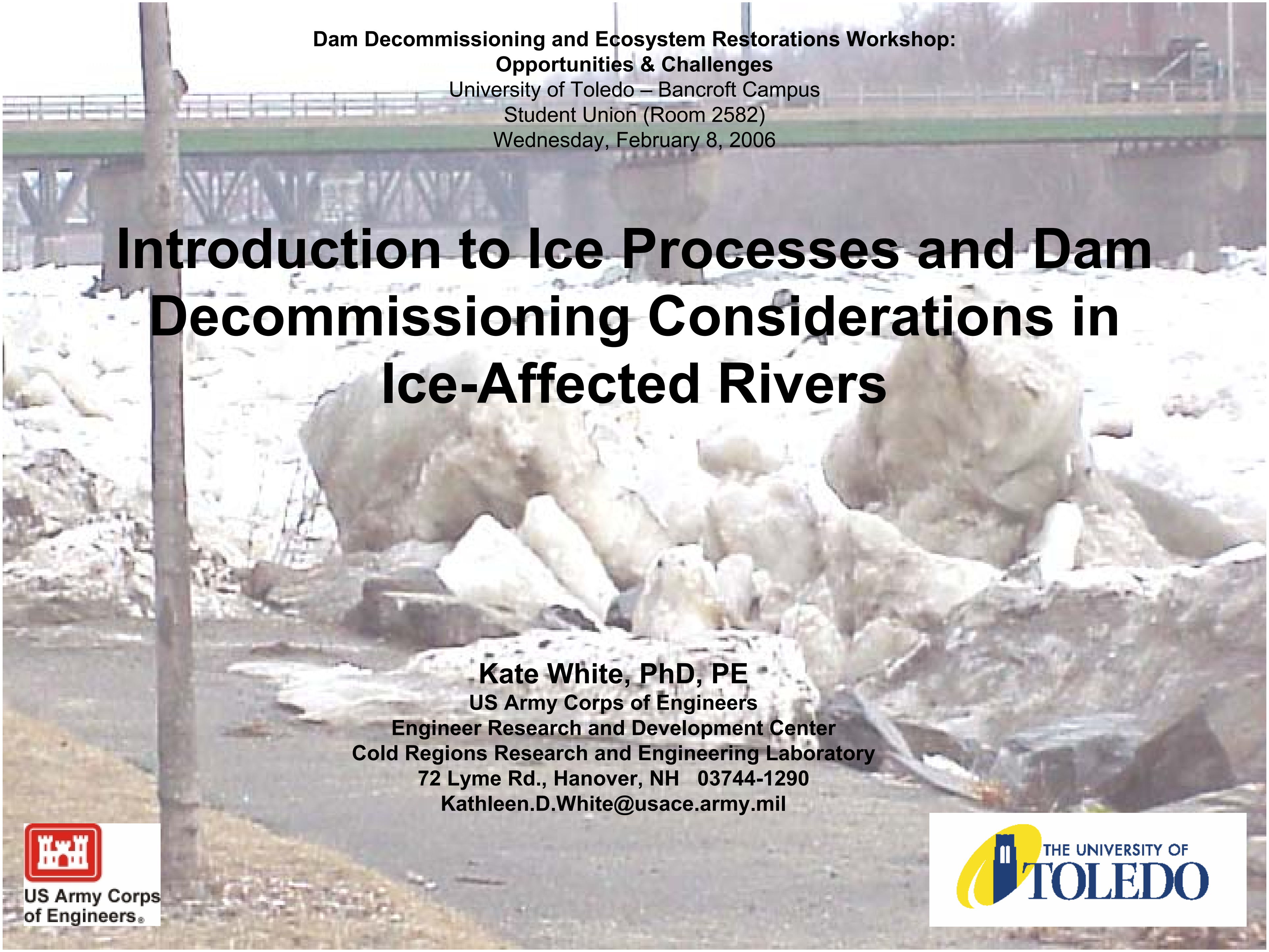

Dam Decommissioning and Ecosystem Restorations Workshop:
Opportunities & Challenges
University of Toledo – Bancroft Campus
Student Union (Room 2582)
Wednesday, February 8, 2006

Introduction to Ice Processes and Dam Decommissioning Considerations in Ice-Affected Rivers

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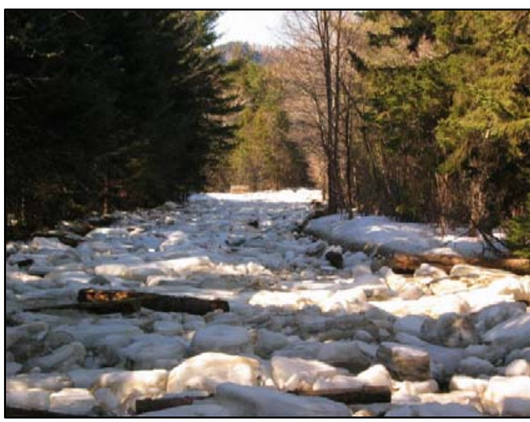
Outline

- Introduction
  - Winter conditions often neglected in planning for dam decommissioning
    - Ice regime
    - Sediment/scour
- Ice Processes
  - Freezeup
  - Breakup
  - Jamming
- Dam Removal Effects
- Case Studies:
  - Salmon River
  - Kennebec River
  - Israel River
- Recommendations

Introduction to Ice Processes

- *Objective:* Develop an understanding of ice processes that lead to ice jam floods
- *Short-Term Goal:* Using a shared vision and common language to describe ice jams will result in better understanding of ice regime impacts
- *Long-Term Goal:* Identify potential reasons why the ice problem exists and how the ice problem may respond to natural or human-induced interventions



Major Concern: Ice Jams Causing Flash Flooding

- NWS definition:
  - A flash flood is a rapid rise in water levels associated with heavy rainfall or the failure of a dam or ice jam
- Theoretical process:
  - Ice cover forms on river
  - Increase in discharge supplies energy to system:
    - raising stage
    - breaking and moving ice
  - Transport capacity of river exceeded:
    - ice stops moving (jams) $\Rightarrow$ backwater
    - shoving and thickening due to incoming ice increase thickness at jam toe $\Rightarrow$ higher stages upstream (lower stages downstream)
    - jam progresses upstream

Aerial view of the Montpelier 1992 flood. Cover photo of the *Ice and Water* book.

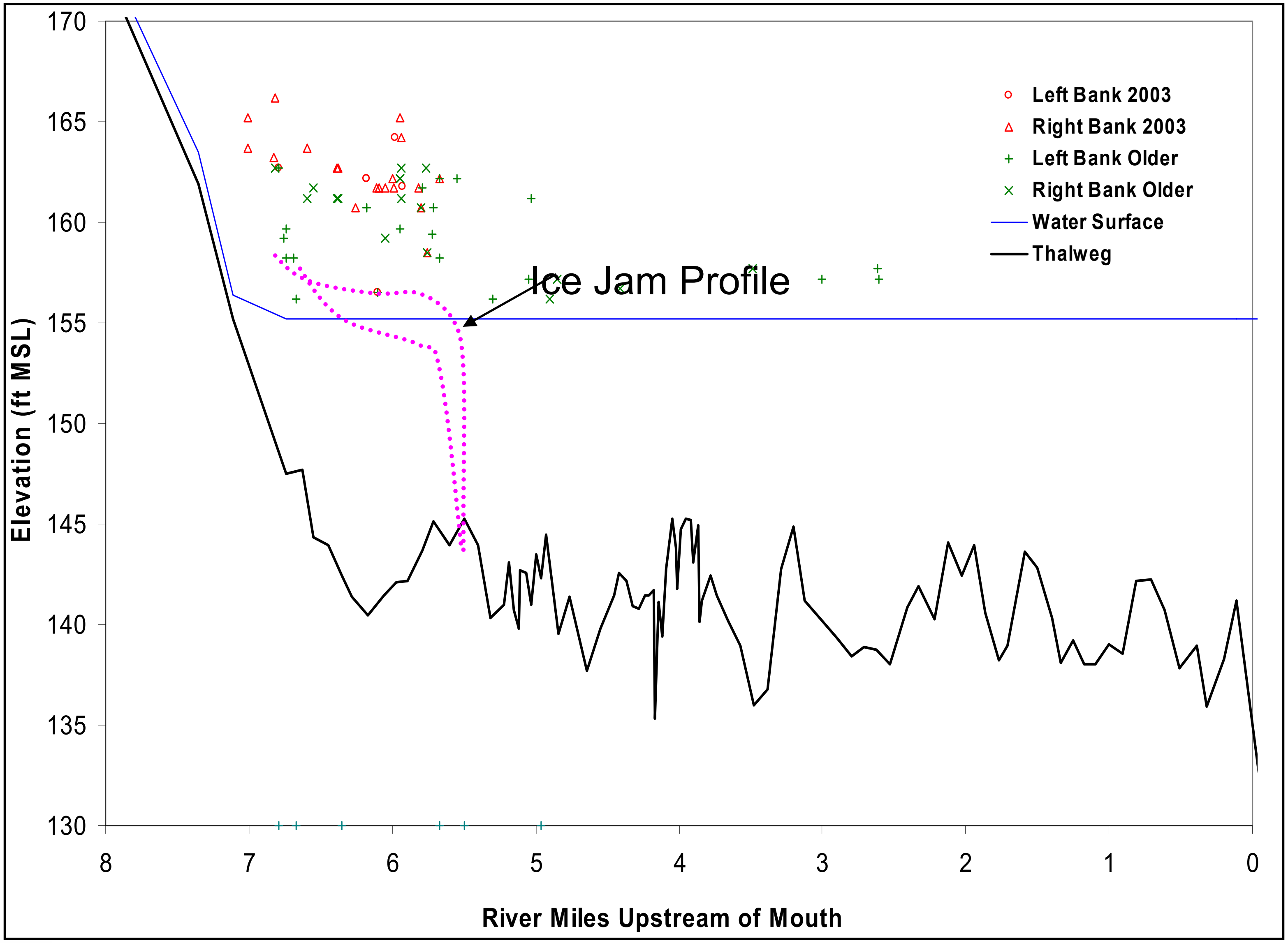
Jim Cole, Associated Press
Copyright 1992 "Ice and Water" Committee

Flash Flood Example: Montpelier, VT

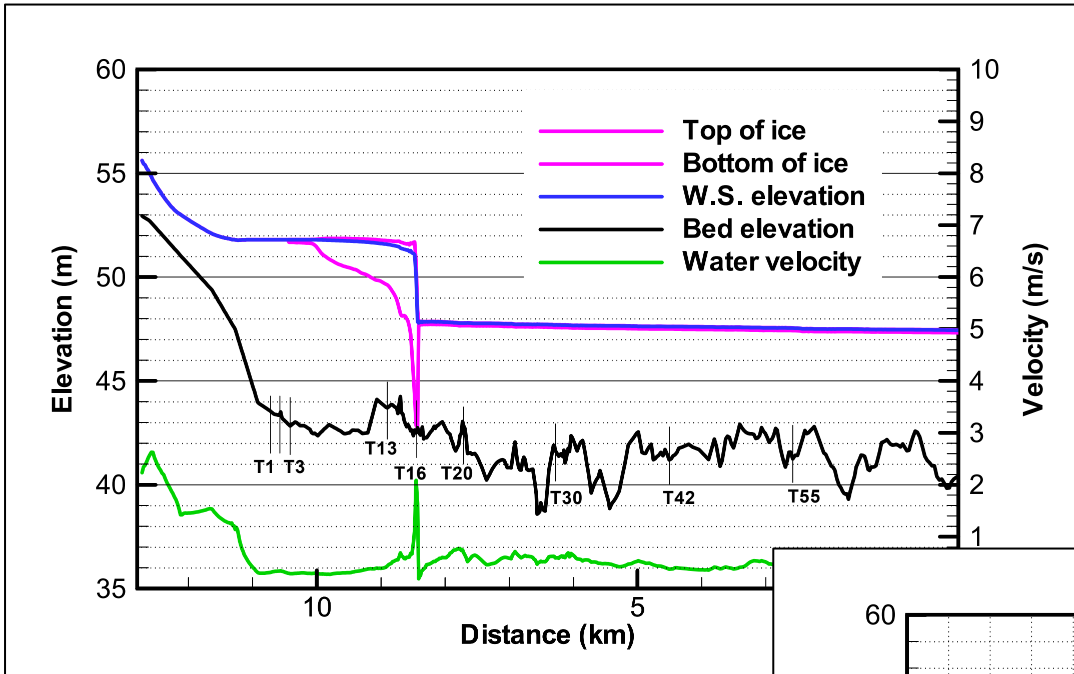
Wednesday, March 11, 1992

- **6:57 a.m.** A large ice jam on the Winooski River breaks loose about the Pioneer Street Bridge and travels through Montpelier. Ice jams just below the Bailey Avenue Bridge and dams the river.
- **7:05 a.m.** Filled with rain and snowmelt, the Winooski begins to overflow its banks along State Street and the North branch begins backing up onto Elm Street.
- **7:15 a.m.** Water surges dramatically into low-lying areas behind Main and State Streets, floating propane tanks from moorings, flooding parked cars and inundating store basements.
- **7:23 a.m.** Radio stations are notified of a flood emergency as first warnings are issued.
- **7:45 a.m.** Icy flood waters hit the steam heating boiler at MacPherson's Travel on Main Street and the boiler explodes, shattering the glass storefront and destroying the basement.
- **7:56 a.m.** Two to three feet of water is reported in front of Days Inn on State Street where an estimated 100 people are stranded. Flood waters pour onto Main Street, stalling cars and making the road impassable. Backed-up water from the swollen North Branch flows upstream on Elm Street.
- **8:09 a.m.** Evacuations begin of hundreds of stranded residents, workers and state employees on Main, State and Elm Street. Some wade to safety, while others are taken out by boat or by fire engines and dump trucks.

Ice Jam Stages >> Open-Water Stages for Same Discharge



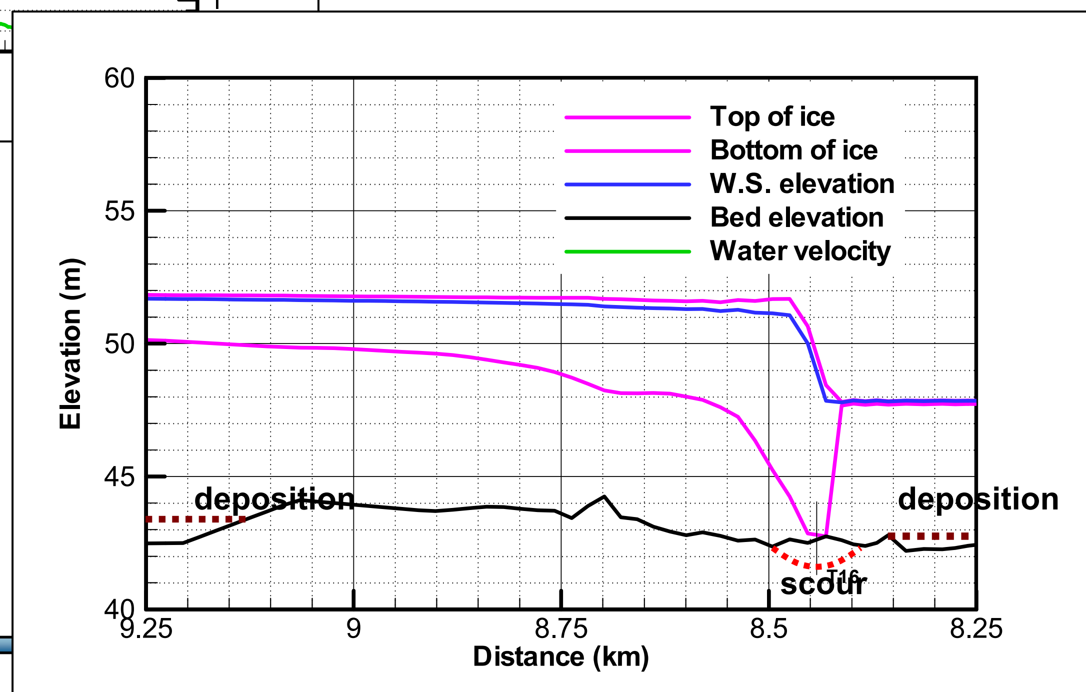
Ice Jam Related Sediment Transport



Jam may thicken to the point of grounding and the moving ice may mechanically scour the river bed

Ice jam can result in high water velocities near the bed

Scour may occur beneath the toe with deposition possible upstream and downstream of the jamming location



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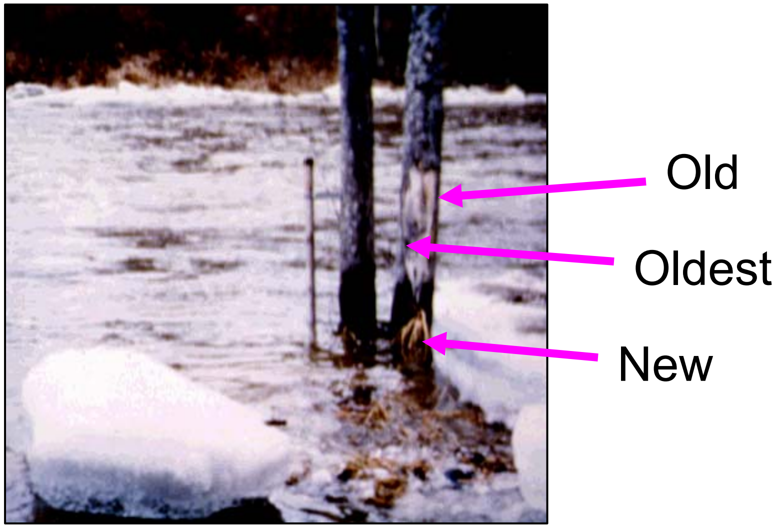
Tree scars

- Earliest record in ice jam database:
  - Montpelier, VT, 1785 as cited by Johnson, 1928

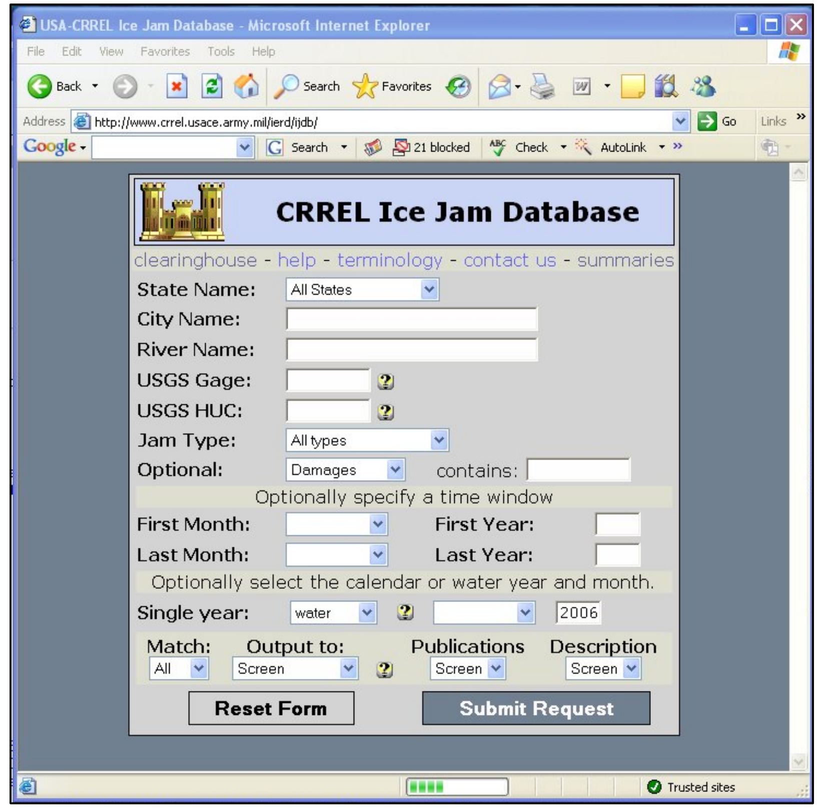
"When the first settler, Jacob Davis, came in 1787, he and those with him **saw on the tree trunks by the river's side the marks of ice which had gone out in a recent freshet**. These settlers were experienced woodsmen and they unanimously decided that it occurred two years before when no one was here to observe it. Mr. Davis always stated that had a flood come after his arrival in Montpelier equal to the flood in 1785, the water would have been 12 feet deep in the roads. Of course the roads then were somewhat lower than the streets are at the present time so probably such a flood now [1928] would bring about eight feet of water."



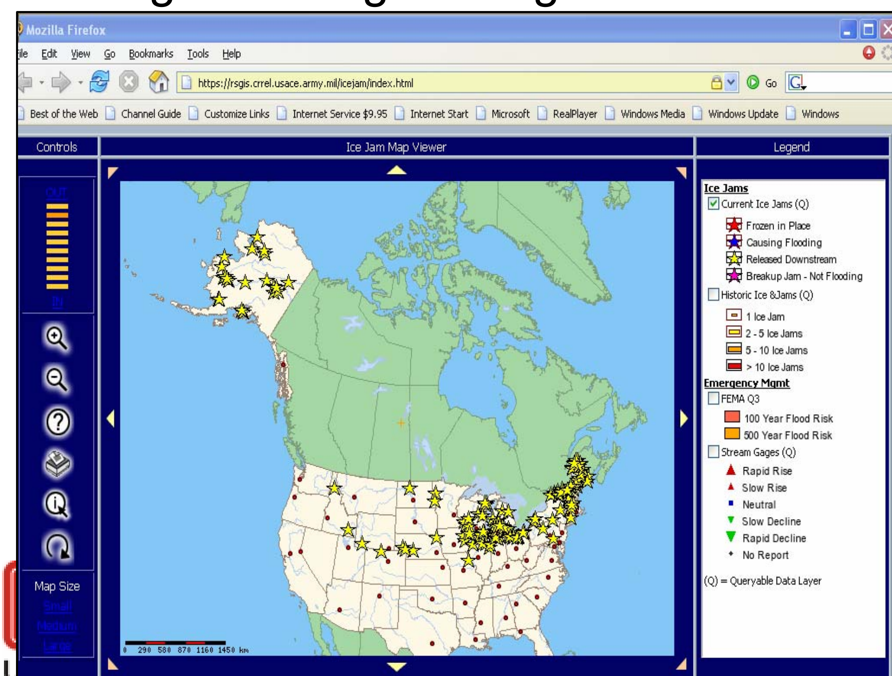
CRREL Ice Jam Database

Major source of data: CRREL Ice Jam Database

- Database begun 1990
- Now >14,900 events (Ohio=511)
- 1785-2006
- Ice information available from text-based database or rapid mapping tool
- Emergency management, design and engineering studies

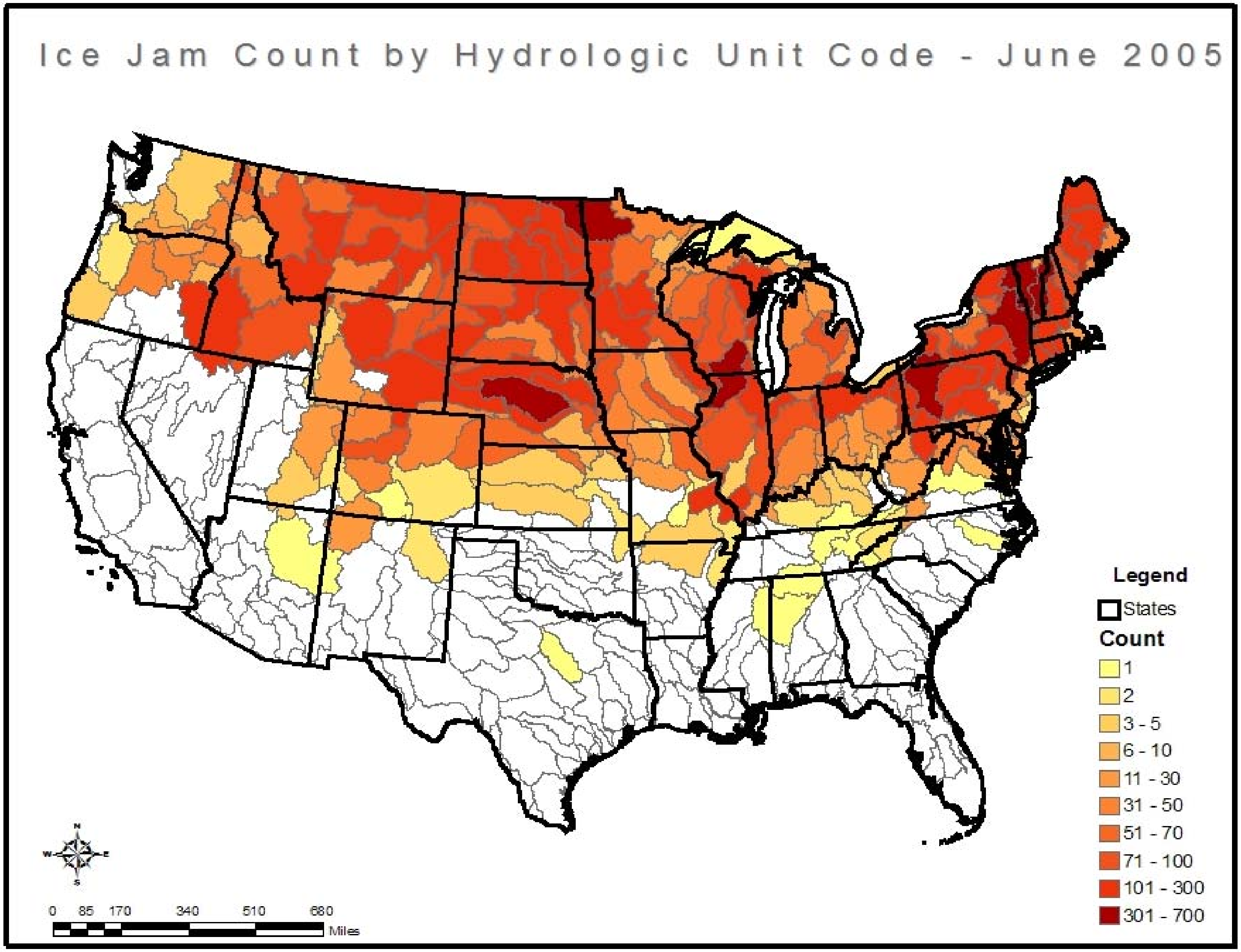


http://www.crrel.usace.army.mil/ierd/ijdb/



Select "Current ice jams" from
http://www.crrel.usace.army.mil/icejams/index.htm

Ice Jam Occurrence



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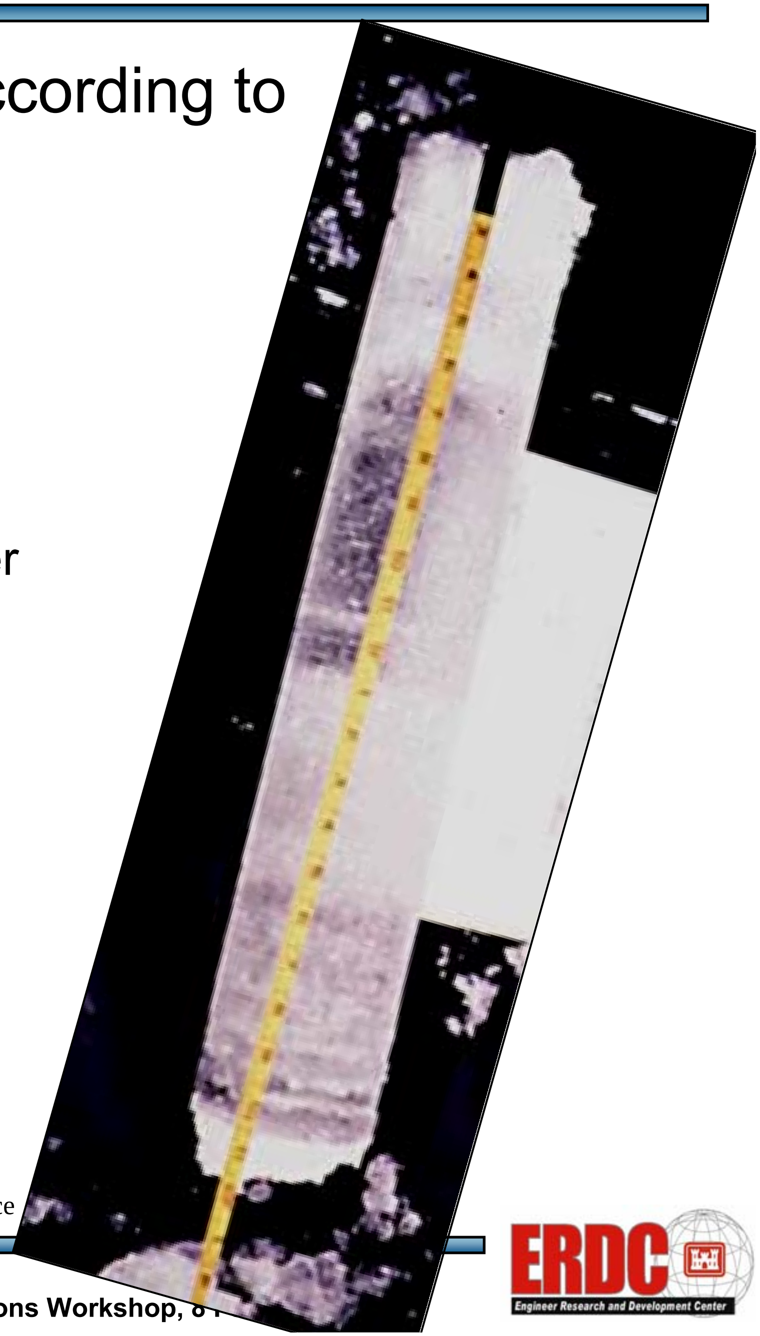
Basic Ice Processes: Formation

- The 2 basic ice types are classified according to their ice crystal structures
  - Columnar ice: Thermally-grown ice
    - Thermally grown
    - “Black” ice
    - Transparent, allows solar penetration, becoming "candled” as it decays
    - Tends to occur in more quiescent flow
    - Can estimate thickening using heat transfer theory
  - Fine grained ice: Frazil ice
    - Small ice particles or snow
    - “White” ice
    - Resists solar penetration
    - Tends to occur in dynamic, turbulent flow
    - Found in virtually all ice-affected rivers
    - Predominant ice type in northern rivers



Core from Israel River, Lancaster, NH, showing both thermal and frazil ice

Thermal Freezeup

- Thermally grown ice (velocity ~ 0 – 1 ft/s)
  - Pools and slow reaches, ice cover grows in from channel sides
  - Can predict thickness based on accumulated freezing degree days using modified Stefan Equation (EM 1110-2-1612)

http://www.usace.army.mil/inet/usace-docs/eng-manuals/cecw.htm

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Ice Engineering

U.S. Army Engineer Research and Development Center, Hanover, New Hampshire

Method to Estimate River Ice Thickness Based on Meteorological Data

Some knowledge of ice thickness is required for the design of structures—such as bridges, dams, weirs, locks, piers, intakes, channel stabilization measures, and coastal shoreline protection—in ice-affected rivers. One recent case illustrating the need for considering ice in the design of riverine structures is the failure of the McKeesport (Pennsylvania) Marina on the Youghiogheny River in January 2001 (Fig. 1 [Silver and Fuoco 2001] and 2). The marina was constructed in 1997 at a cost of more than $2 million. According to the ERDC-CRREL Ice Jam Database sources (National Weather Service 2001a, b; Veltri 2001), ice jam breakup, jamming, and failure resulted in the complete destruction of the marina by chunks of ice measuring up to one foot thick. Contemporary reports estimated that the damage began around 6:30 p.m. on 31 January, and by 8:37 p.m., the marina was torn away. Reconstruction costs for the marina have been estimated at more than $1 million.

Figure 1. Twisted docks at McKees Point Marina on the Youghiogheny River, Pennsylvania. Photo by Darrell Sapp, Post-Gazette.

Ice covers and ice jams can cause rapid increases in stage that can cause flooding and damage (Fig. 3). Numerical models of rivers to develop stage-frequency information required for modeling ice jams for flood damage reduction measures, flood insurance studies, and changes to the ice regime that occur from development in the floodplain or dam removal also require that ice thickness be estimated. Analyses of ice-induced scour and erosion in ice-affected rivers must include knowledge of ice thickness.

Unlike discharge or stage measurements, observations of ice thickness can be challenging to locate. The USGS does record ice thickness as part of its winter discharge measurements, but these records are often archived in paper form and can be difficult to access. Some local flood warning systems measure ice thickness. A good example is the Nebraska Ice Warning System (http://dnrdata.dnr.state.ne.us/Icejam/index.asp), which contains seasonal ice thickness measurements.

Given the lack of existing data, ice thickness must often be estimated. Because ice covers result from complex physical processes, there is not yet a method to account for all factors affecting thickness. This technical note presents a method to estimate ice thickness that results from heat transfer processes based on meteorological data.

Figure 2. Debris from the McKeesport Marina trapped above Emsworth Locks and Dam on the Ohio River about six miles downstream from Pittsburgh. Photo by Andy Tuthill, ERDC-CRREL.

ERDC/CRREL Technical Note 04-3 **June 2004**

http://www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/TN04-3.pdf

EM 1110-2-1612

-EH

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

EM 1110-2-1612

0-2-1612

30 October 2002

Engineering and Design
ICE ENGINEERING

ose. This manual, composed of three parts, pre... design, construction, and operation and mainten... for Corps of Engineers projects; provides in Par... the resultant flooding, including preventive mea... eering and operational solutions to ice problems

icability. This manual is applicable to all USA... sign, construction, operations, and maintenance.

ibution statement. Approved for public relea...

rences. Bibliographic material is included at th...

ussion. All Corps projects subjected to freezing... n lock walls, hydropower intakes, and lock appr... ice passage over spillways that scours the down... and shorelines, etc. Therefore, ice control meas... projects to improve operations and safety in cold... n of ice formation processes, physical properties,... nsiders the problem of ice jams and ice jam flood... Part III of this manual addresses the considerati... s, including the conduct of river ice management... ent plans.

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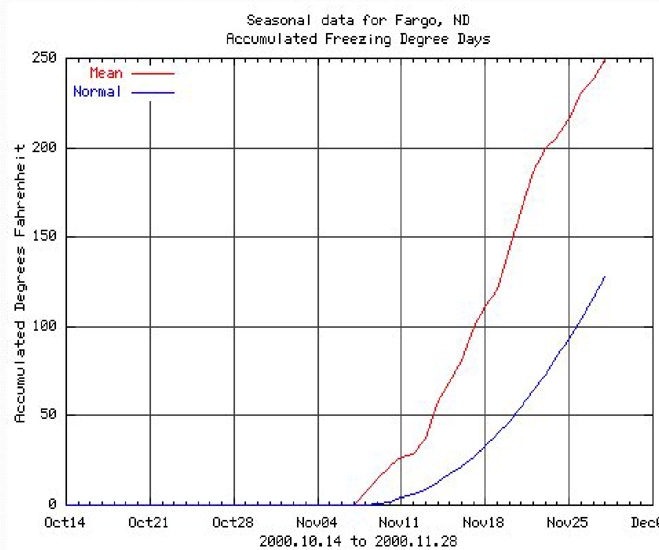
JOSEP...
Colone...
Chief...

ual supersedes EM 1110-2-1612, dated 30 April

Seasonal AFDD Query Results



Seasonal AFDD: 249 Fahrenheit Normal AFDD: 128 Fahrenheit
Ice thicknesses for various conditions using the Stefan Formula:

Theoretical value:	16.2 inches or 41.2 cm ($K = 35$)
Windy lakes with no snow:	12.5 inches or 31.8 cm ($K = 27$)
Average lake with snow:	9.5 inches or 24.1 cm ($K = 20.5$)
Average river with snow:	6.7 inches or 17.1 cm ($K = 14.5$)
Sheltered small river with rapid flow:	4.9 inches or 12.3 cm ($K = 10.5$)

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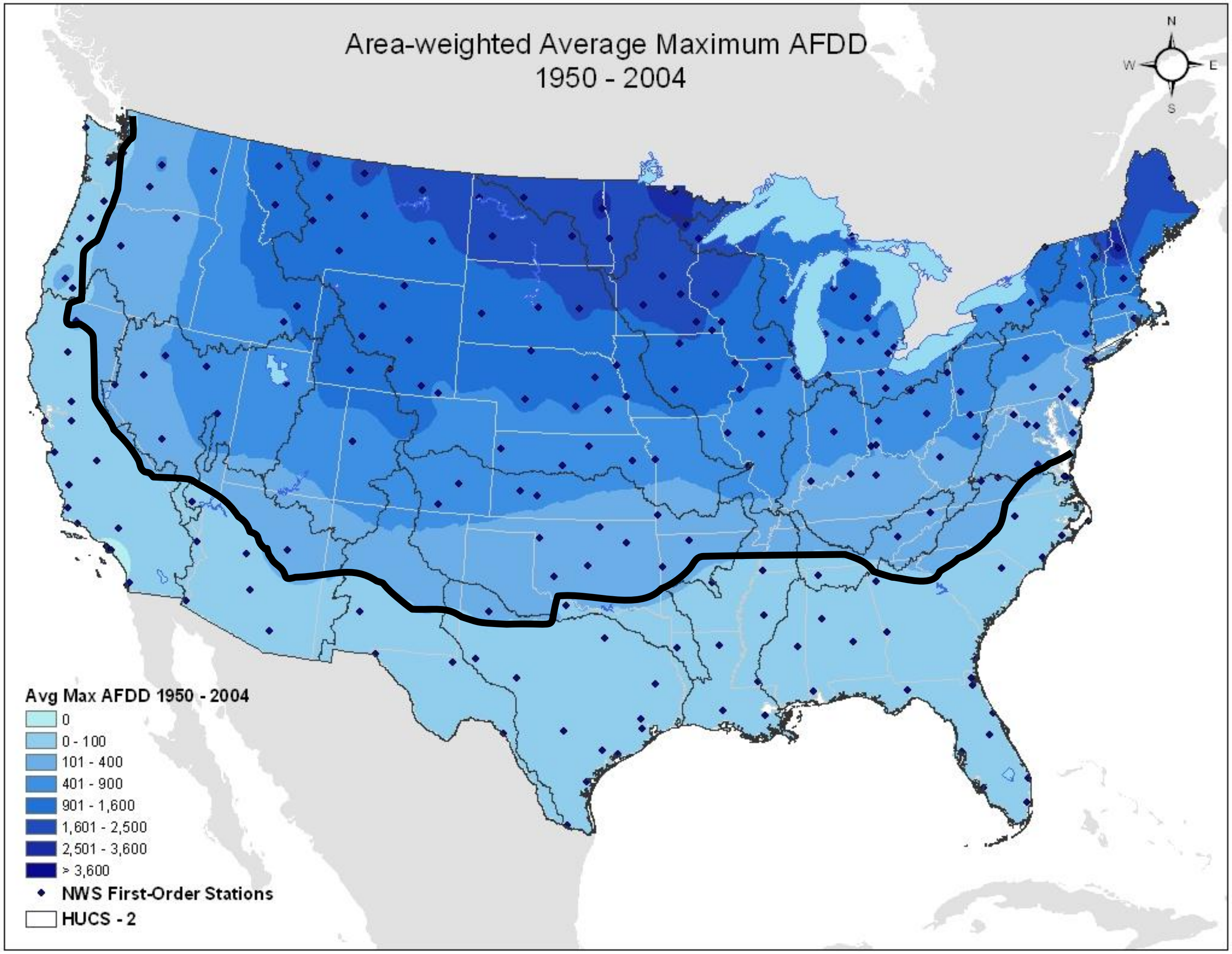
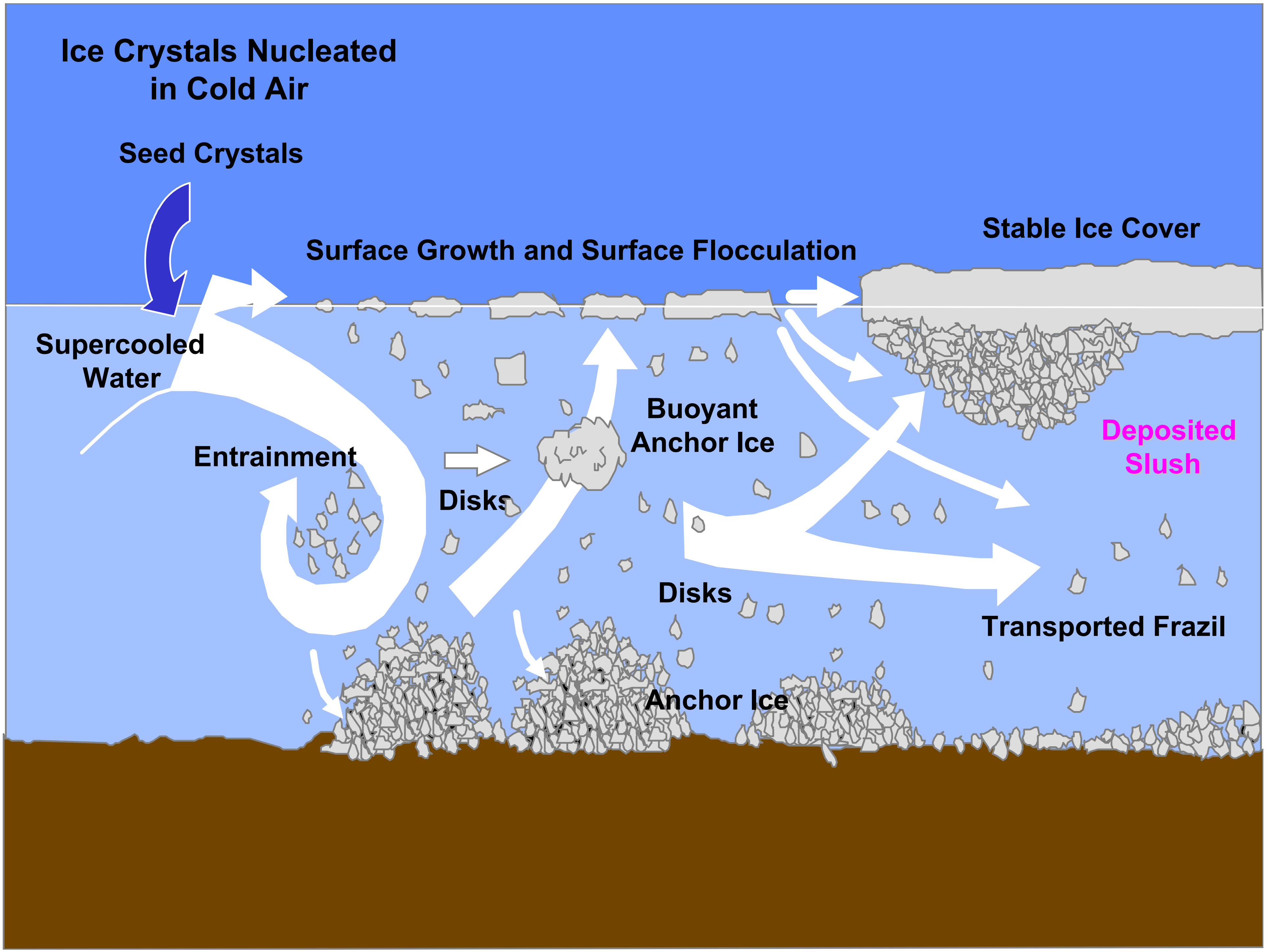
http://www.mvp-wc.usace.army.mil/ice...

Average Maximum AFDD (1950-2004)



Dynamic Freezeup

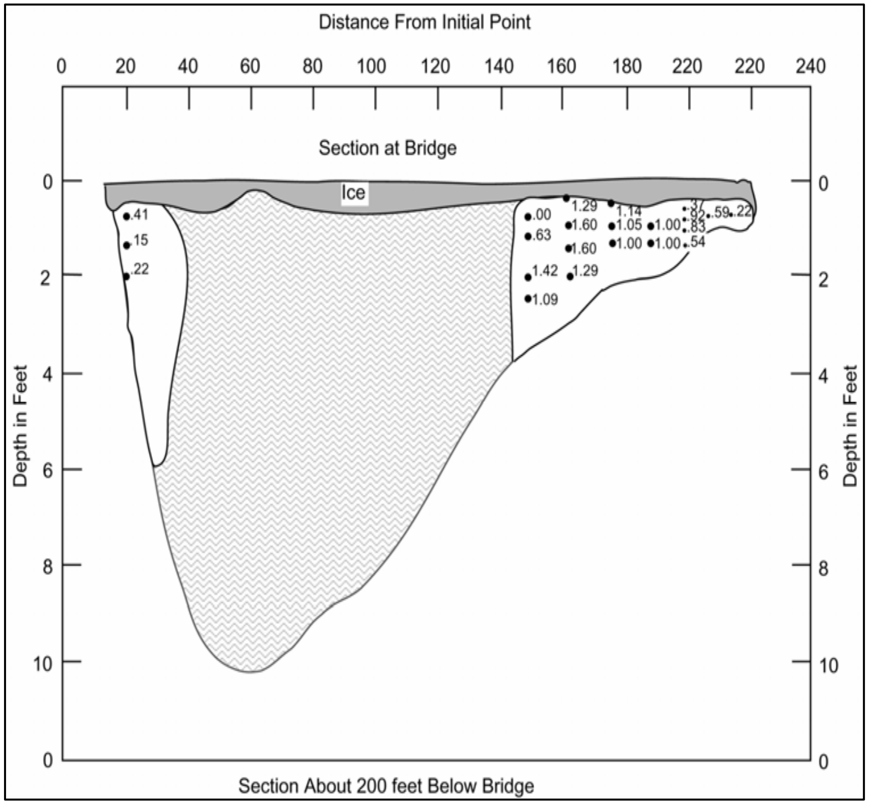
- Dynamically grown ice (frazil ice)
  - Drifting frazil slush or anchor ice
  - Frazil ice floes: pans or pancakes
  - Juxtaposed frazil floes “freezeup ice cover” (velocity ~ 1 – 2.2 ft/s)
  - Shoved frazil ice floes “freezeup ice jam” (velocity ~ 2.2 – 4? ft/s)
  - Entrained frazil slush or “underturned” floes (v > ~2.2 ft/s)
  - Frazil deposition beneath freezeup ice cover or jam



Ice Crystals Nucleated
in Cold Air
Seed Crystals
Surface Growth and Surface Flocculation
Stable Ice Cover
Supercooled
Water
Entrainment
Disks
Buoyant
Anchor Ice
Deposited
Slush
Disks
Transported Frazil
Anchor Ice

Frazil Ice Deposition

- Where to look for it:
  - Change in slope from steep to mild
    - Upstream end of impoundments
    - Confluence of smaller and larger tributary
  - Downstream from locations that are turbulent enough to remain open most of the winter (e.g., tailrace, rapids)
- What are the physical implications?
  - Thicker ice takes longer to break up than thinner ice
  - Potential jam location
  - Increases ice volume compared to no deposition
- When to be concerned about thicker than normal frazil deposition:
  - Sudden period of intense cold when there is little to no ice cover to insulate water surface

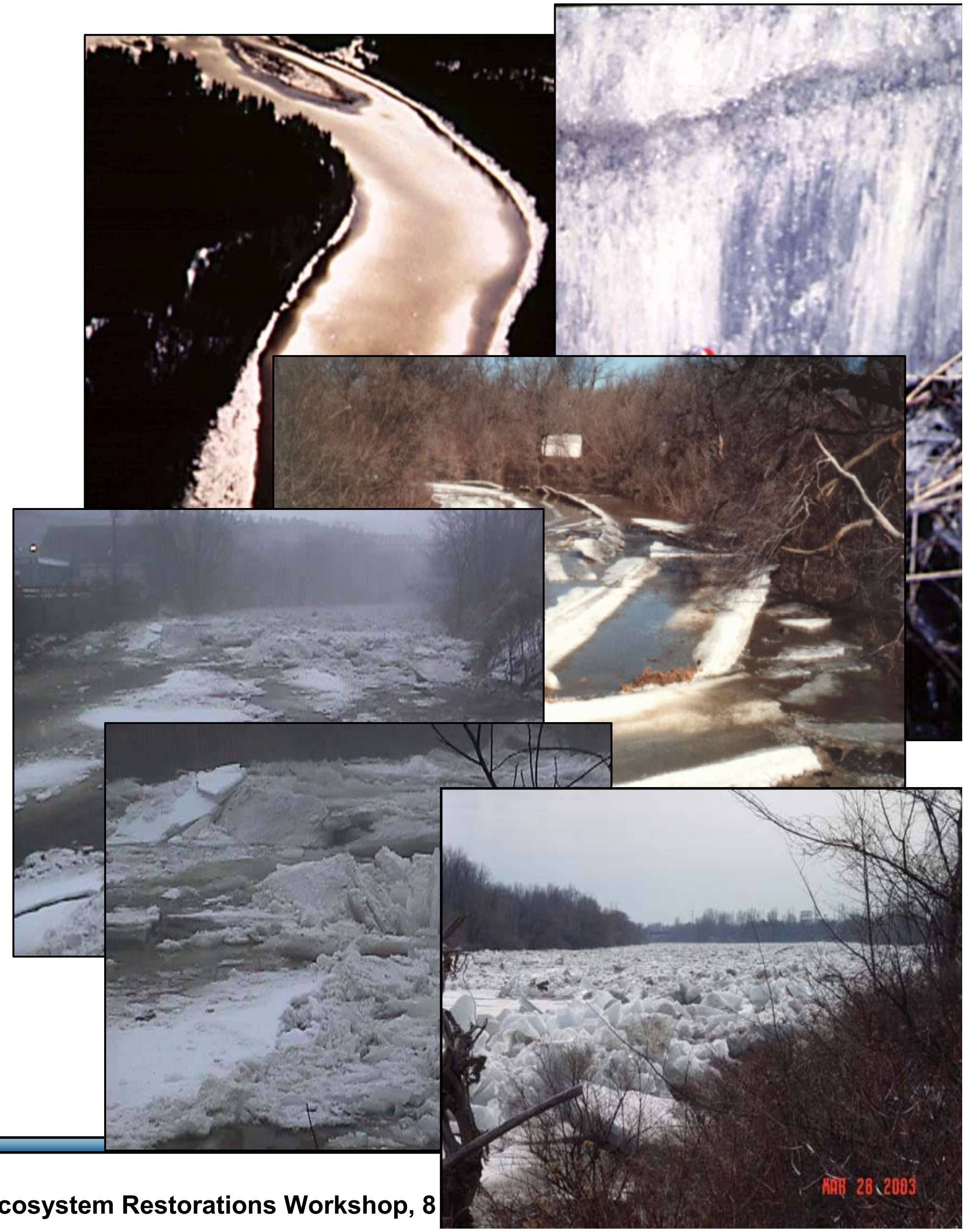


Chemung River, NY (after Barrows and Horton 1907)


Ice heaving above water level in river channel
1. 24. 2005 13:08

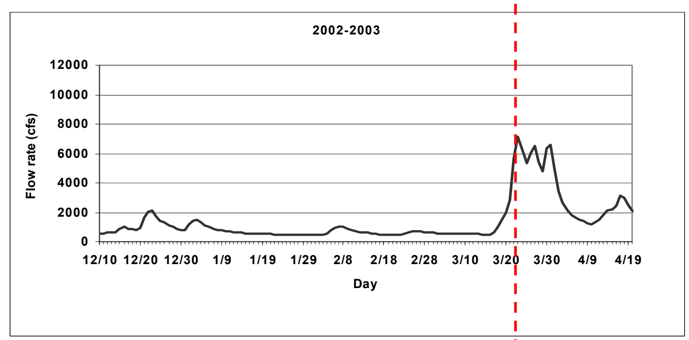
Ice Breakup

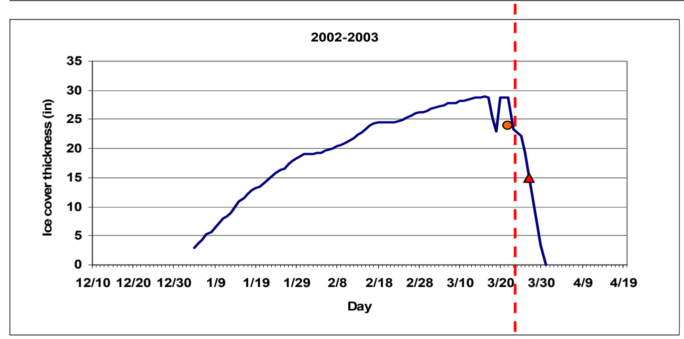
- Continuum from gradual thermal "breakup" to dynamic "mechanical" breakup
- Thermal "Breakup": Ice cover melts in place
  - Long gradual warming period with no significant rain
  - Ice cover thins, weakens and melts in place, or forms minor jams
- Mechanical Breakup: downstream forces on cover exceed restraining forces and ice cover strength
  - Limited warming period
  - Rapid thaw with rainfall
  - Quick rise in river flow and stage
  - Strong thick ice breaks up, runs and jams

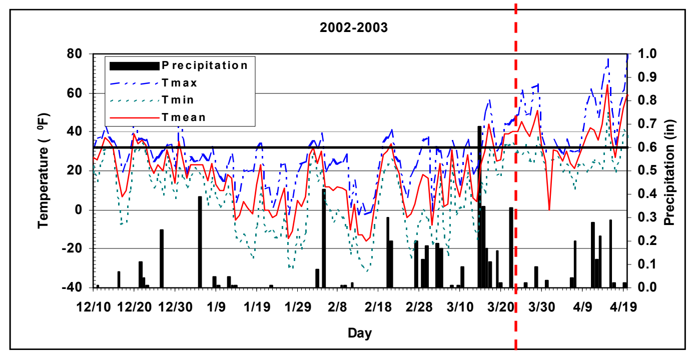


Factors Affecting Ice Cover Breakup

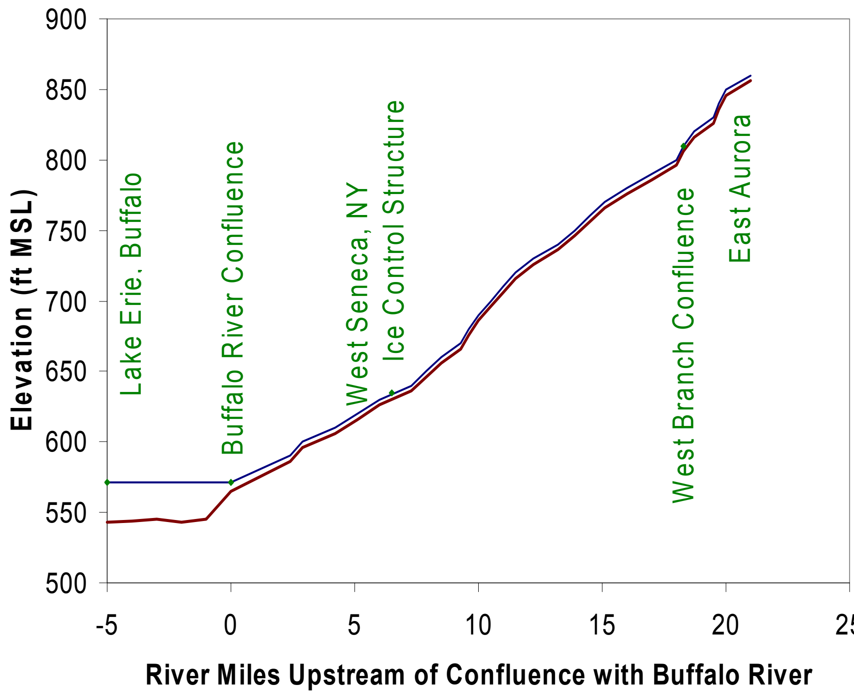
Hydrograph, Ice Thickness (AFDD), Ice Strength, Air Temperature, Snow, Rainfall

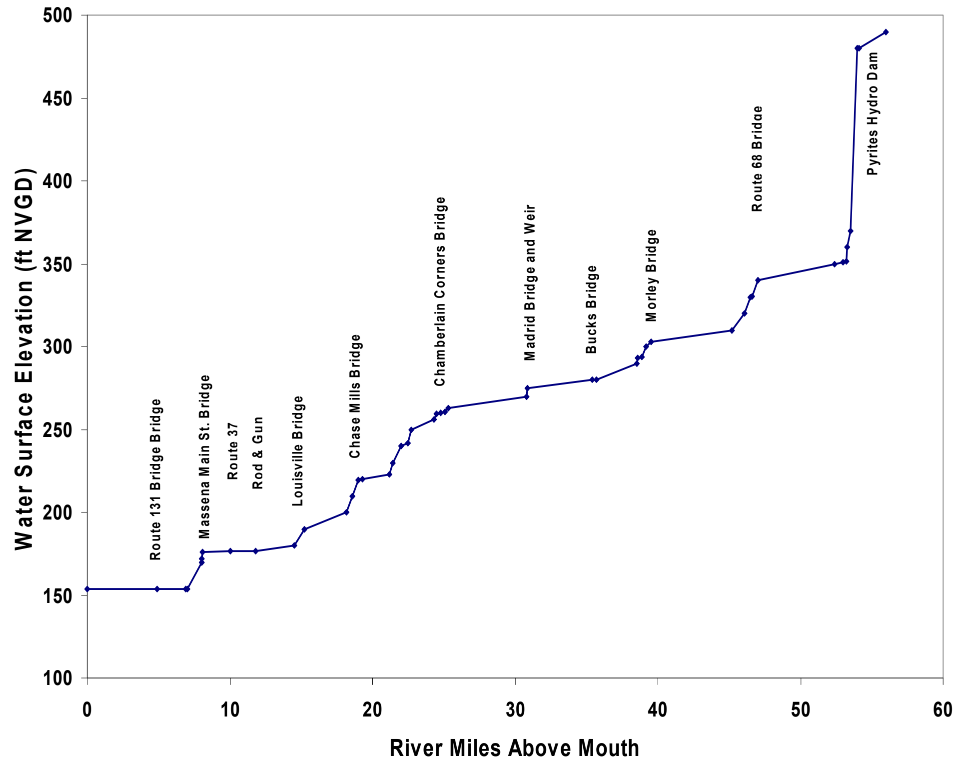






Nature of Breakup Also Depends on River Bed Profile





Continuously steep river grading into flat section near downstream end:
-All ice may run and jam near mouth

Stepped river profile (e.g., small dams):
-Numerous steep sections may break up earlier, forming jams in flatter reaches

Sediment – and ice – tend to deposit at transition points from steeper to milder slope, decreasing ice conveyance and increasing ice jam potential

Typical Ice Jam Locations

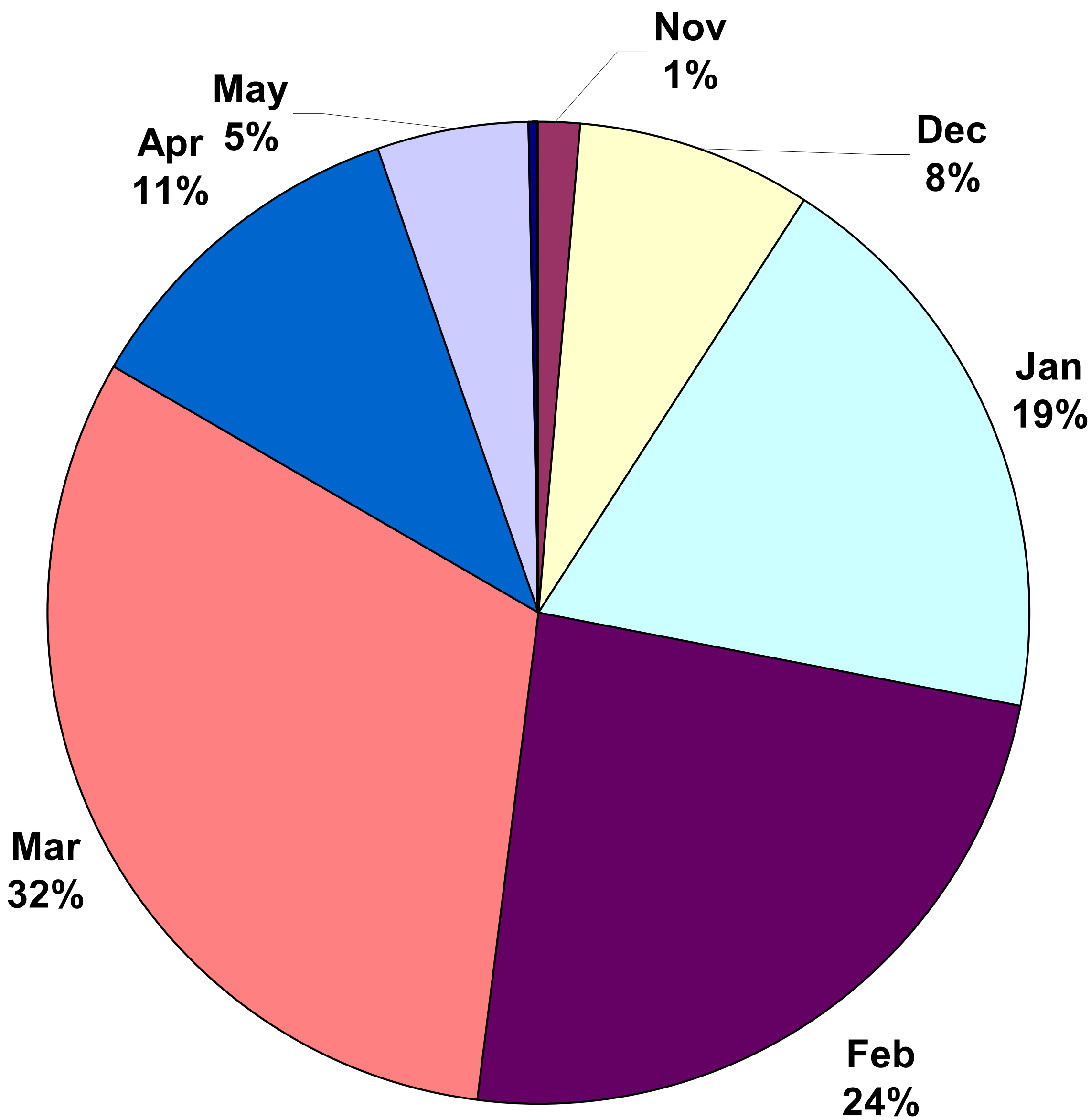
Transition areas from steep to mild slope

Ice jam on the Connecticut River at Windsor, VT above the head of the Bellows Falls Dam impoundment

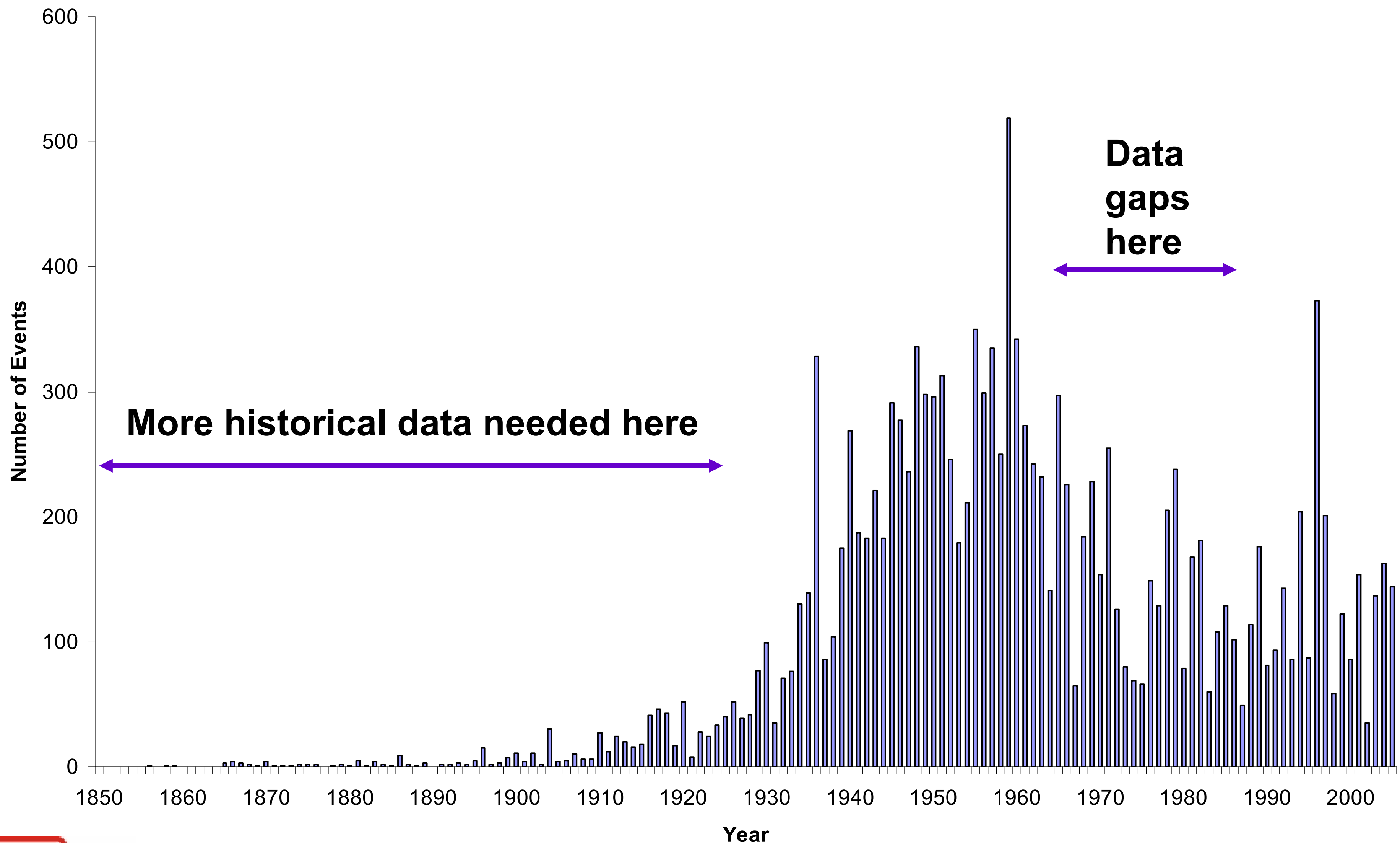
Channel constrictions, bends, and meanders

Ice jam in constricted bend in the Androscoggin River downstream of Canton, Maine

% of US Ice Events By Month

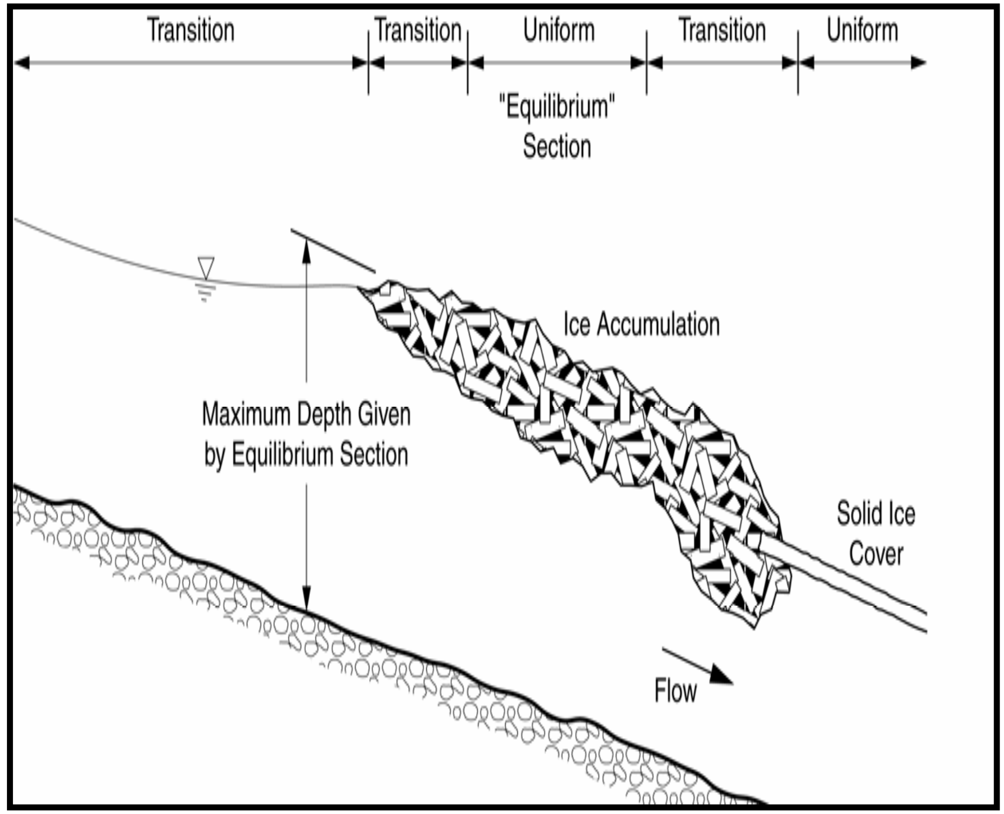


Number of US Ice Events Since 1850



Modeling Ice-Covered Rivers

- Steady Flow
  - HEC-RAS
  - 1-D steady flow
  - Freezeup or breakup
  - Can model deposition using iterative process
- Unsteady Flow
  - Ice routine coming in HEC-RAS
  - UNET
  - Discrete Element Models
- Zufelt (1999) provides test to determine whether steady flow assumptions are violated to the point that unsteady flow is required
- 2 Dimensional Flow
  - DynaRICE
  - Discrete Element Models



Note: Flood insurance studies and re-studies at locations with frequent ice jams should include ice hydraulic modeling, or regulatory floodplain limits may not be conservative enough

Effects of Dam Removal in Ice-Affected Rivers

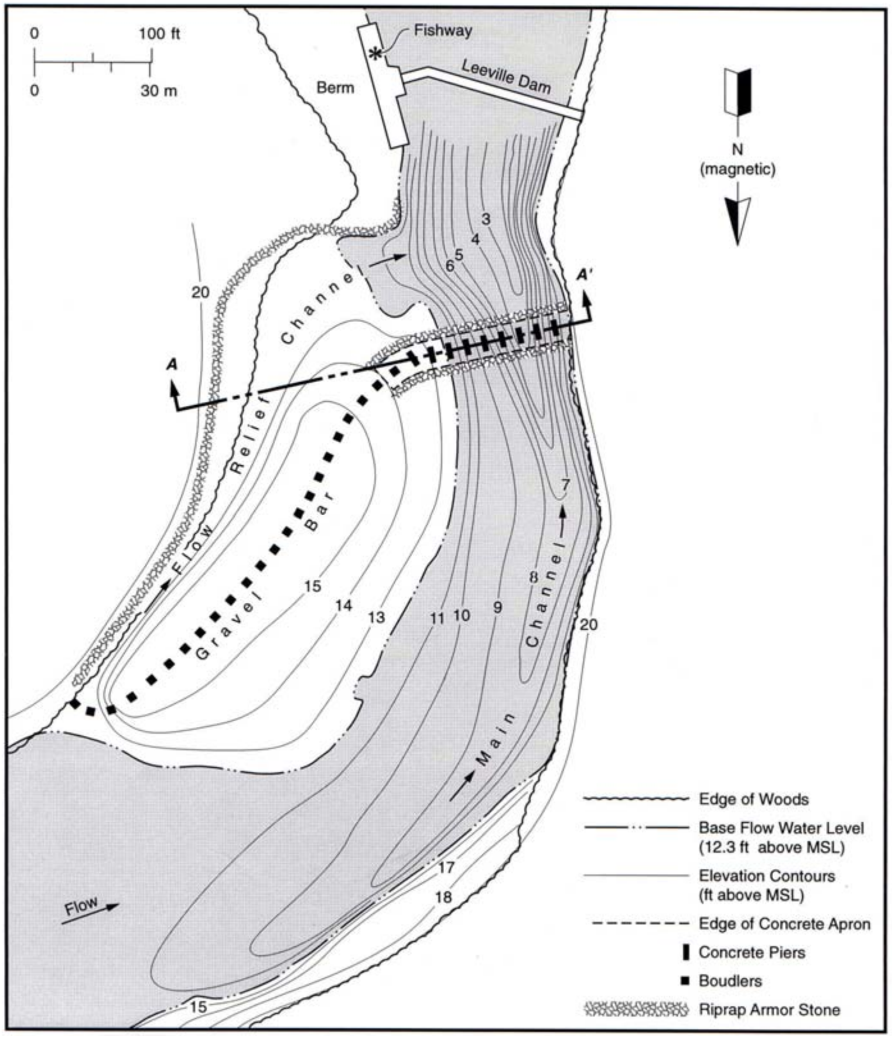
- Can impact location, frequency, severity of ice jams (e.g., Israel River, Lancaster, NH; Edwards Dam, Kennebec River, Augusta, ME)
- Most studies neglect effects on ice regime
  - Frazil transport and deposition
  - Ice cover breakup and transport
  - Breakup jam formation
- Increased frazil production → thicker downstream ice
- Jams that formed upstream from dam may now form downstream
- Downstream jams may increase in frequency and severity
- Increased scour and erosion within former impoundment and at new jam locations

Example:

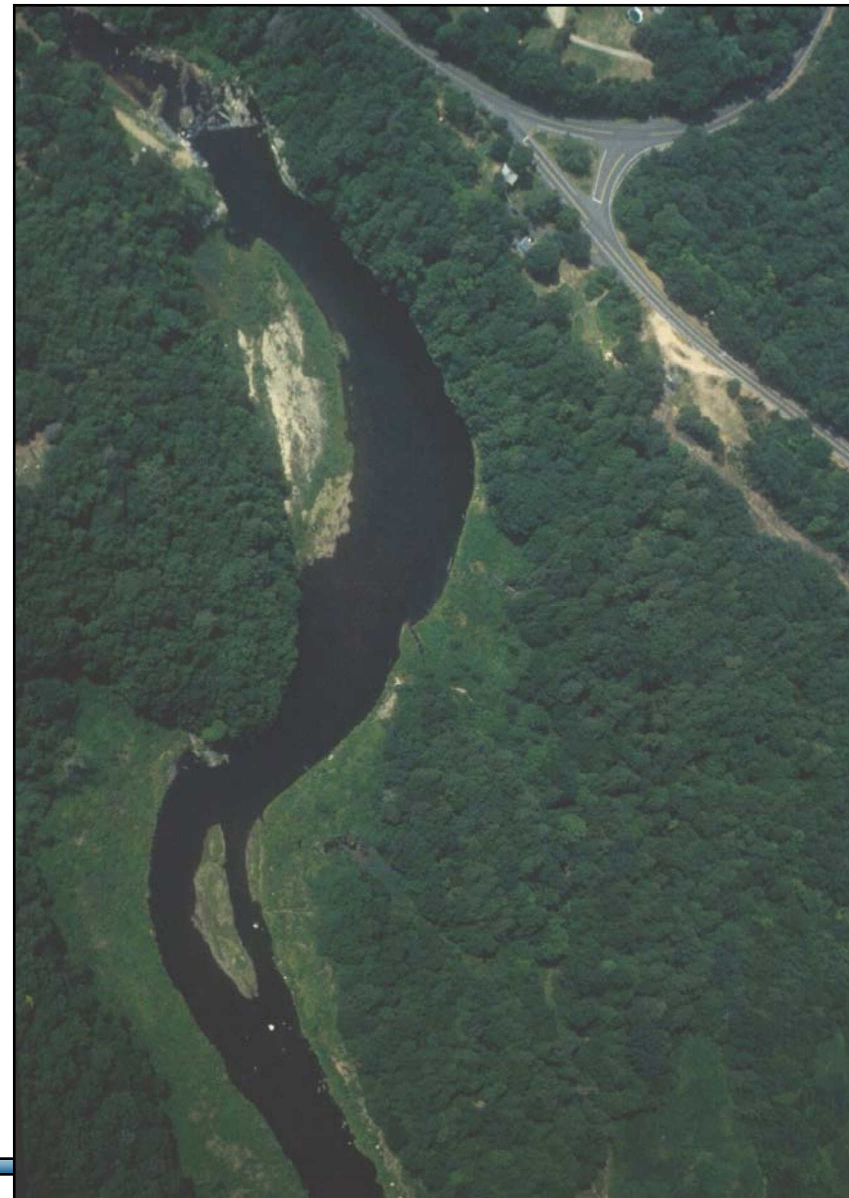
Ice Regime Change Following Decrease in Dam Height, Salmon River at East Haddam, CT

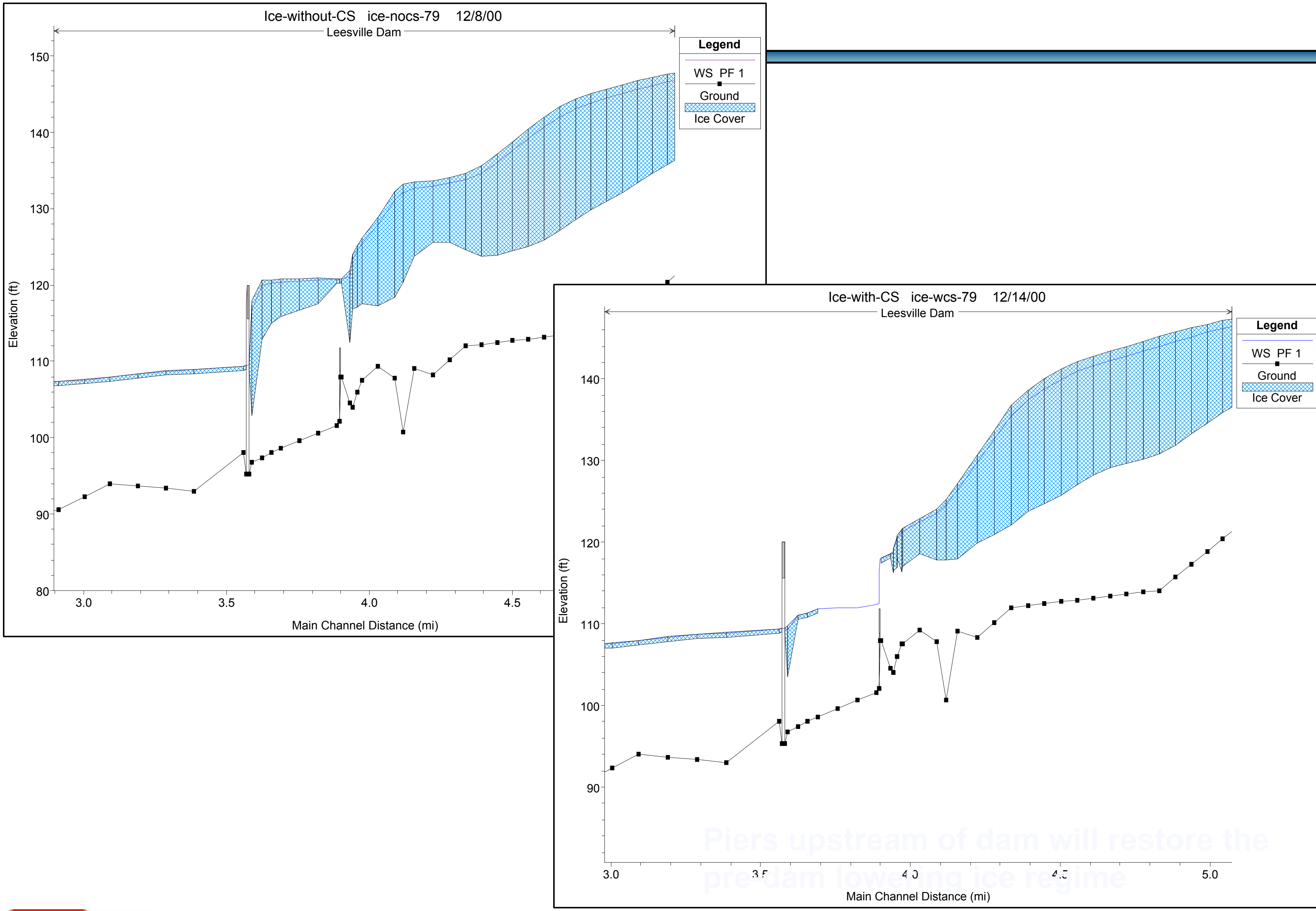
- Known ice jams before present dam construction (in 1941): 1876, 1901, 1910, 1940
- 1901 and 1910 events damaged smaller dams at the site
- Spillway lowered 10 ft, fishway added: 1979-1980
- Damaging jams downstream 1982, 1983, 1994, 1996, 2000
- Sediment transport from former impoundment to downstream estuary under ice and open-water conditions

- Solution:
  – Construct ice control structure upstream from existing dam
  – Construct sediment basin upstream from ice control structure to control sediment movement



0
100 ft
0
30 m
Fishway
Berm
Leeville Dam
N
(magnetic)
A
A'
Channel
Relief
Flow
Gravel
Bar
Main
Channel
Flow
20
3
4
5
6
7
8
9
10
11
13
14
15
17
18
15
20
Edge of Woods
Base Flow Water Level
(12.3 ft above MSL)
Elevation Contours
(ft above MSL)
Edge of Concrete Apron
Concrete Piers
Boudlers
Riprap Armor Stone



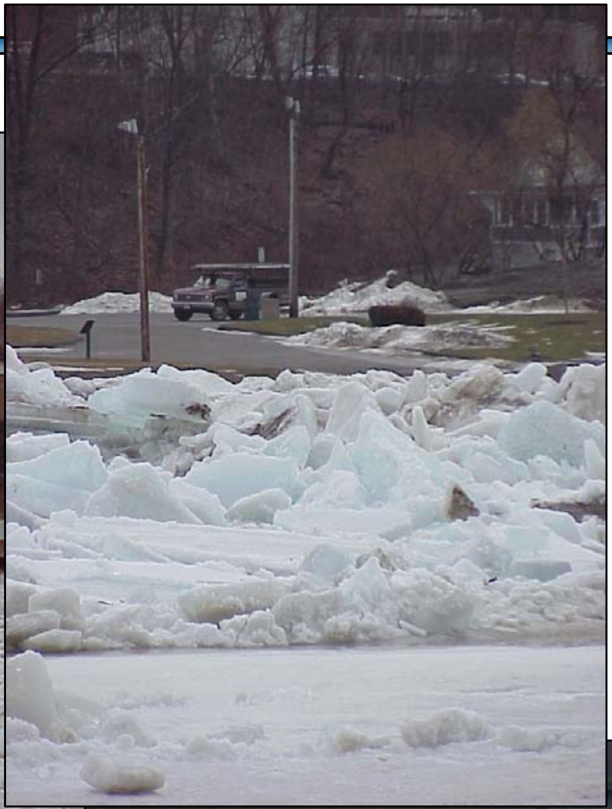


Piers upstream of dam will restore the pre-dam lowering ice regime

Example:

Ice Regime Change Following Dam Removal, Kennebec River at Augusta, ME

- Known ice jams before dam construction: 1794, 1795, 1807, 1826, and December 1835
- 1839 ice run damaged dam
- After completion, damaging jams formed downstream in Hallowell and Gardiner except January 1870, when ice jammed at upstream end of Edwards Dam impoundment, then moved downstream to jam in Hallowell
- Edwards Dam removed in July 1999
- Freezeup jams form annually since dam removal at head of tide
- Breakup jams in 2001 (mild), 2003, 2004



March 26, 2003

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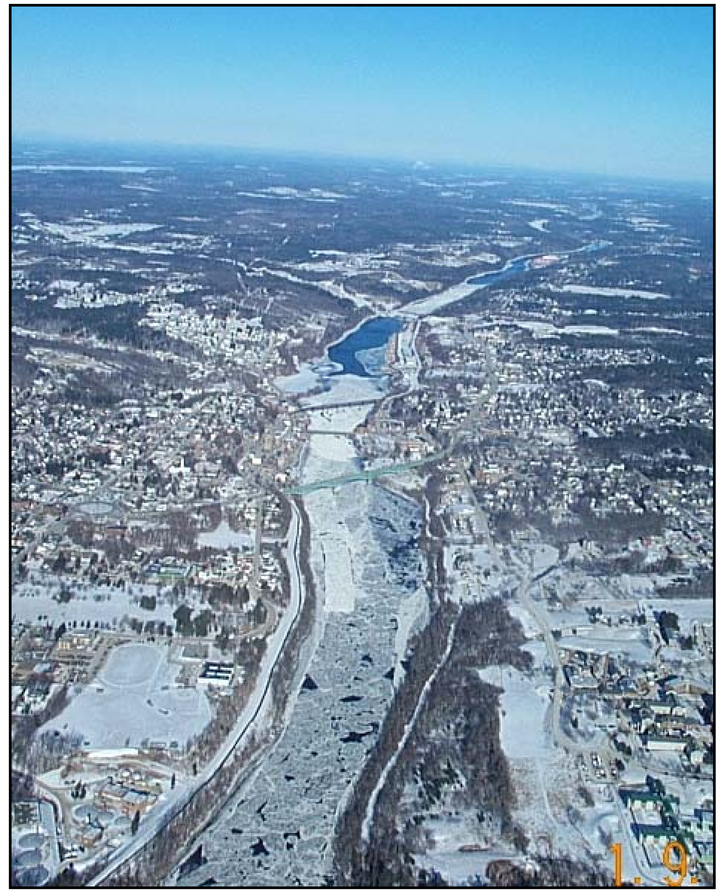
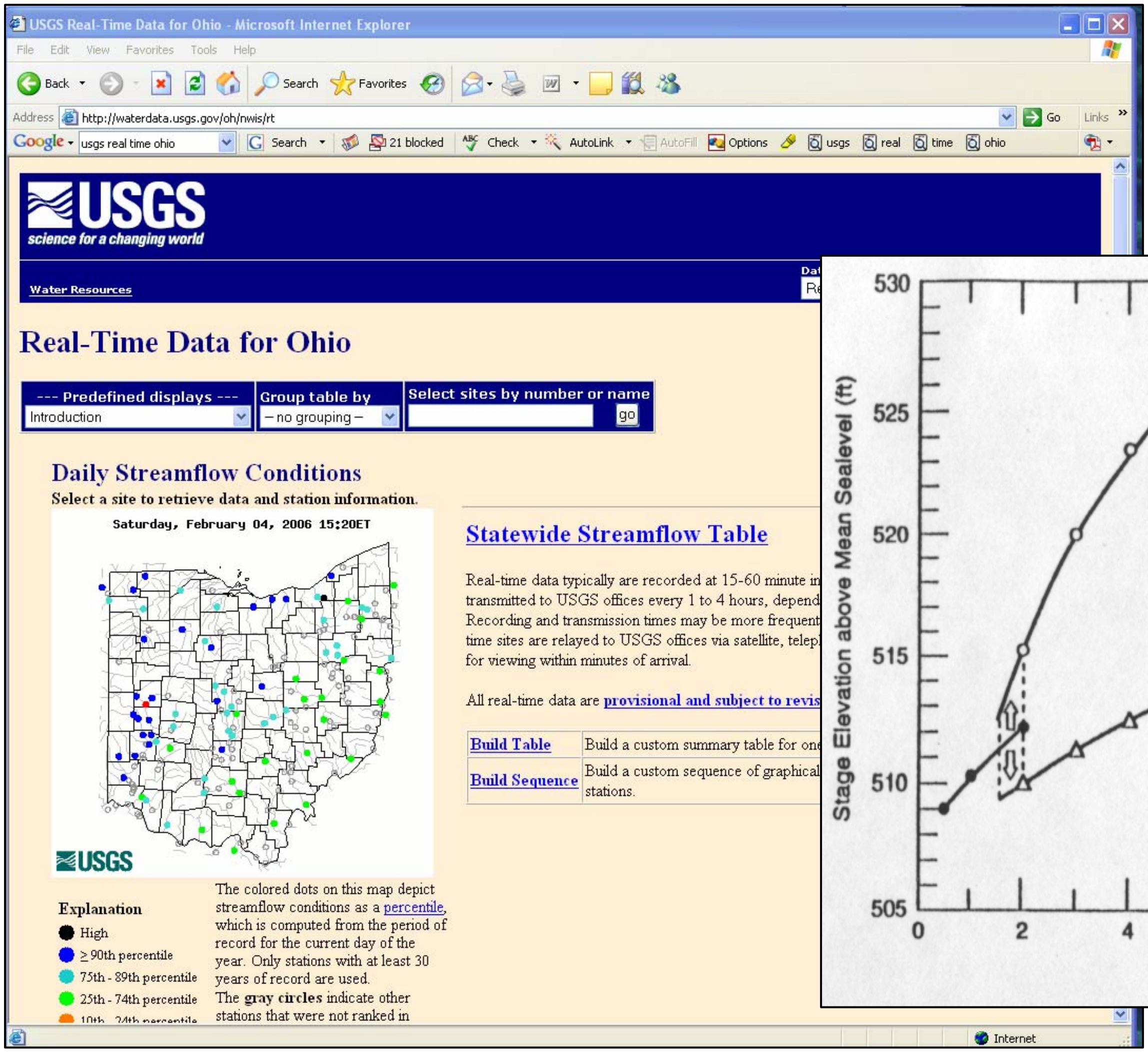
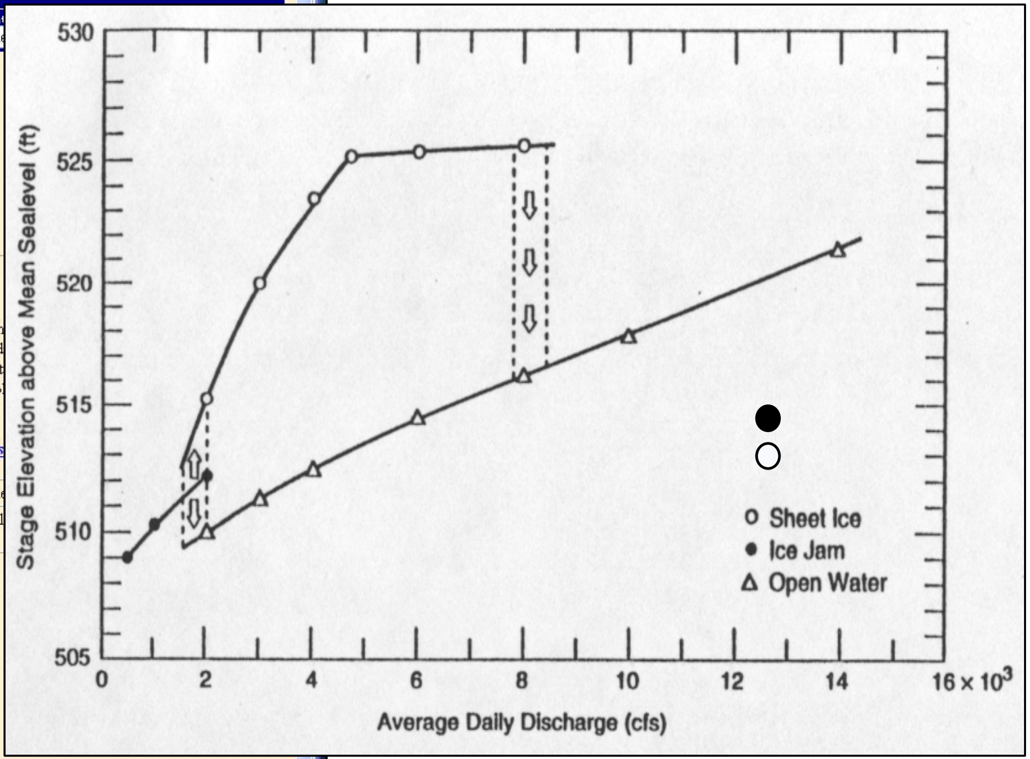
- Quantitative description of changes in Kennebec River due to dam removal is difficult because no comprehensive ice data exists to describe the ice regime before removal
- Qualitative evidence suggests that:
  - When dam was in place, frazil ice previously deposited in impoundment, stopping movement of upstream ice except during extreme flow events (e.g., 1936)
  - Before construction and after dam removal, frazil ice deposits occur at head of tide, forming freezeup jam in Augusta
- Ice control may be necessary to mitigate changes in ice regime



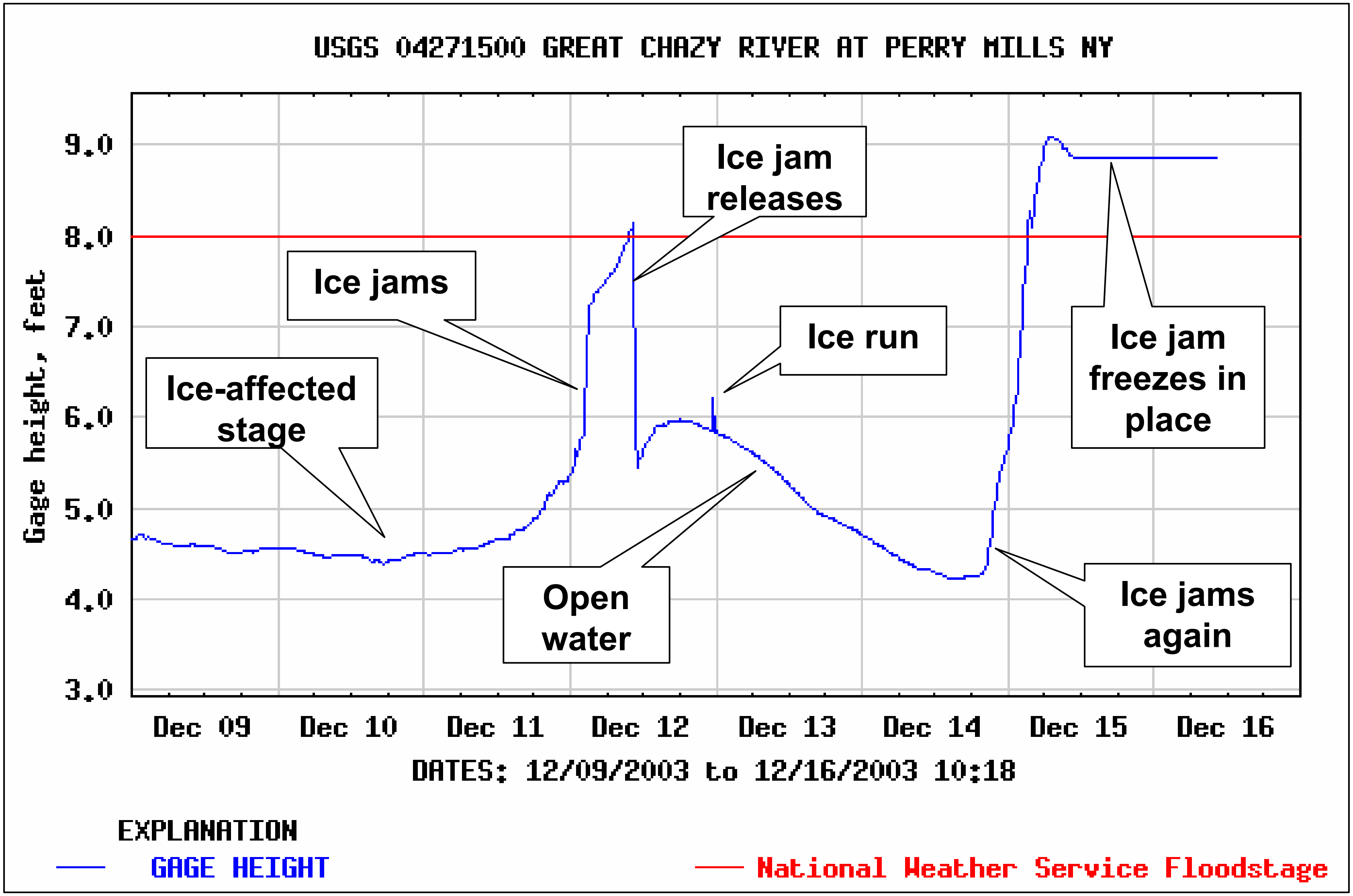
USGS Gage Data for Ice-Affected Stages

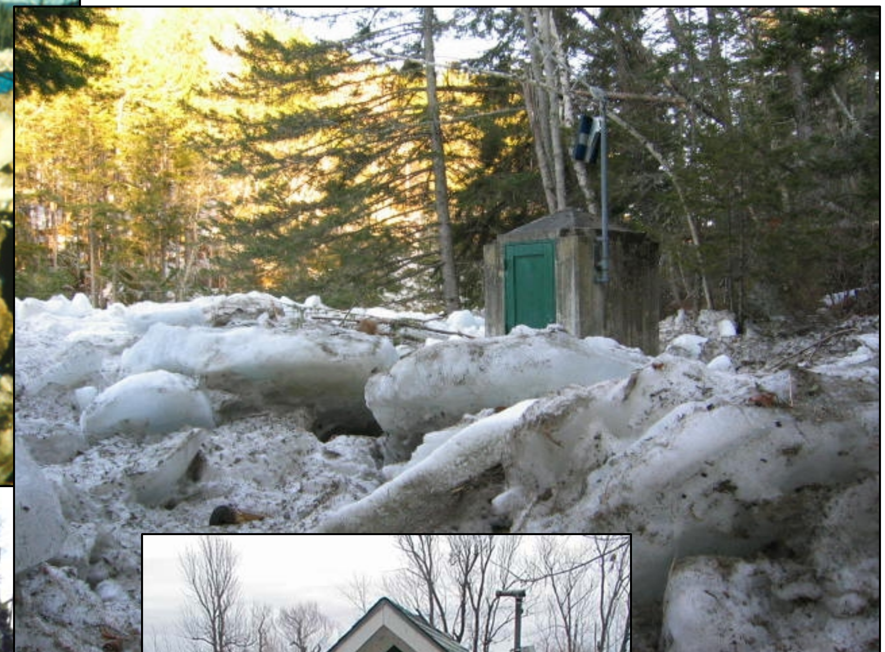




http://waterdata.usgs.gov/oh/nwis/rt

Breakup Jam Followed by Freezeup Jam





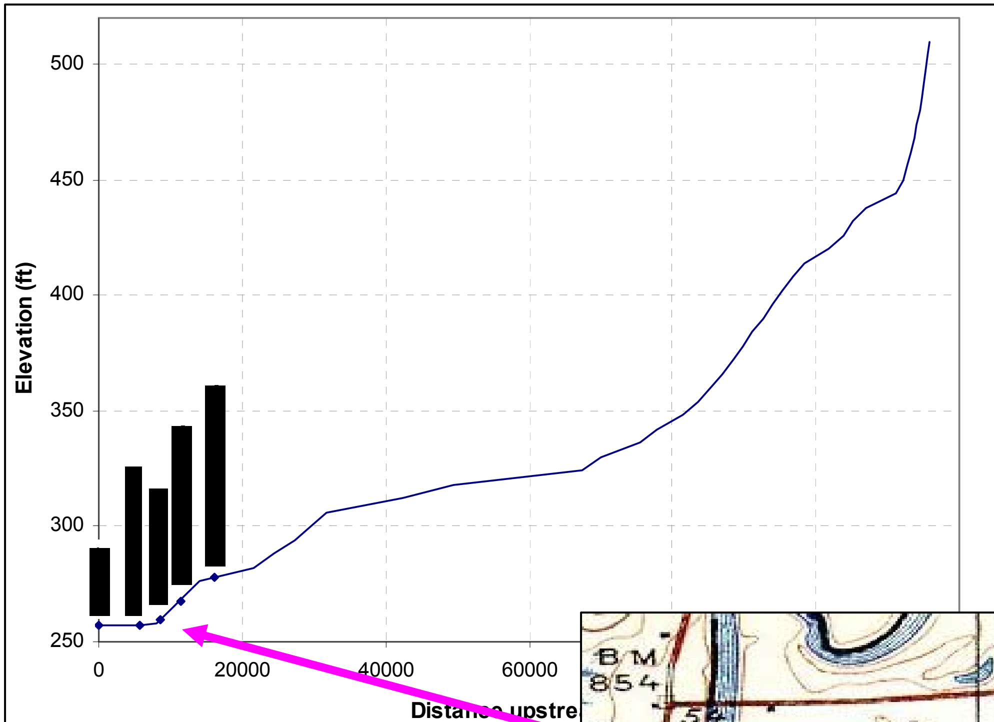

USGS
View of USGS gage
Courtesy USGS Troy NY
January 20, 2006

Example:

Ice Regime Change Following Dam Failures, Israel River at Lancaster, NH

- In the latter 19th and early part of the 20th century, four dams were known to exist within Lancaster
  - 8-ft high timber crib dam (NH#131.01)
  - 20-ft high timber crib dam (NH#131.02)
  - 20-ft high, 220-ft long dam (NH#131.03)
  - 25-ft high timber crib dam (NH #131.04)
  - Ice Formation
- Israel River is about 21 miles long with a drainage area of 136 mi2 at the Connecticut River confluence
  - Average river slope is 0.03; average slope at the confluence is 0.0001
  - The river produces a significant amount of frazil ice in the steep, fast-moving reaches
  - Frazil ice deposits form a thick ice cover in the flat, slow-moving backwater of the Connecticut River
  - Ice as thick at 7’ has been measured in this area

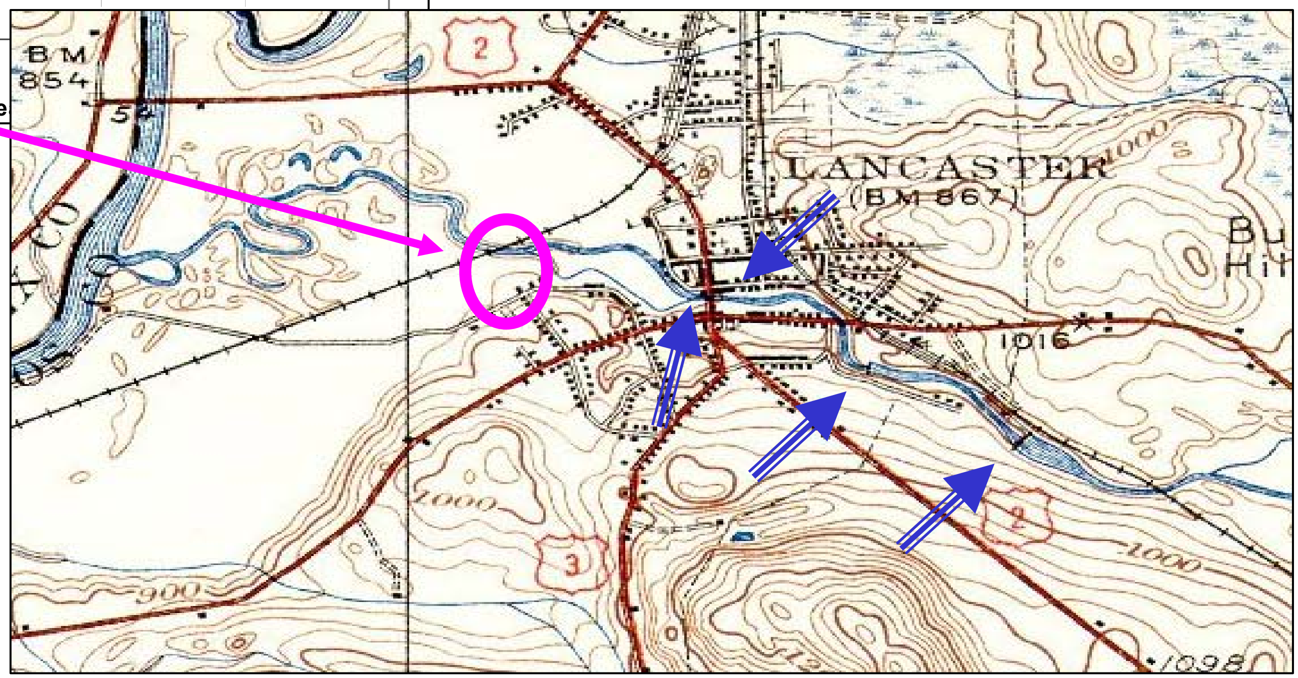
#131.01 and #131.02 (circa 1928)



•Historic flood events

–Between 1870 and 1940, 2 flood events were caused by ice jams

–Following several significant flooding events, 4 dams in downtown Lancaster failed between 1936 and 1950



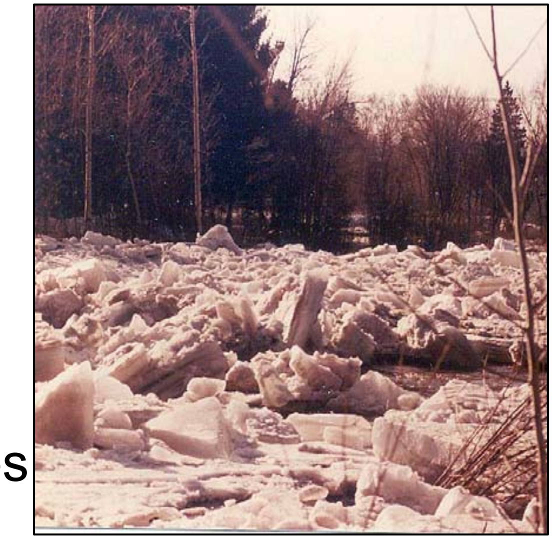
1936

Ice Jams → Ice Control Structure

- Between 1940 and 1970, 15 ice jam flooding events occurred
- The flood of record occurred in 1968 and was caused by an ice jam which resulted in a flood stage 3' higher than the worst open-water event
- As in many northern locations, the removal of these dams has impacted the ice regime, and resulted in increased frequency and severity of jams
- Beginning in 1964, with added urgency following the flooding in 1968, the Corps of Engineers New England Division (NAE) and the Cold Regions Research and Engineering Laboratory (ERDC-CRREL) performed a detailed study that resulted in the design of an ice control structure (ICS)
- The ICS as constructed as a 160 ft long, 9 ft high concrete-capped gabion weir with four sluiceways intended to enhance fish passage
- The ICS was completed in 1981
- The Israel River ICS was originally designed to serve as an ice retention structure during breakup, plus to reduce the amount of frazil in the Israel River that can contribute to the thick ice cover in the backwater of the Connecticut River

Ice Control Structure

- In the late fall stoplogs or bar racks placed in the sluiceways to form a pool
  - solid thermally- grown ice cover forms in the pool
  - frazil ice deposits
- Later in the winter, pool level drops, providing storage
- The thicker ice upstream from the ICS, requires more energy breakup and move than the thinner ice covers upstream
- More energy is also required to lift the ice cover over the ICS
- The ICS acts as an obstruction to ice passage downstream, delaying the contribution of upstream ice to the jam at the Connecticut River confluence



February 1985

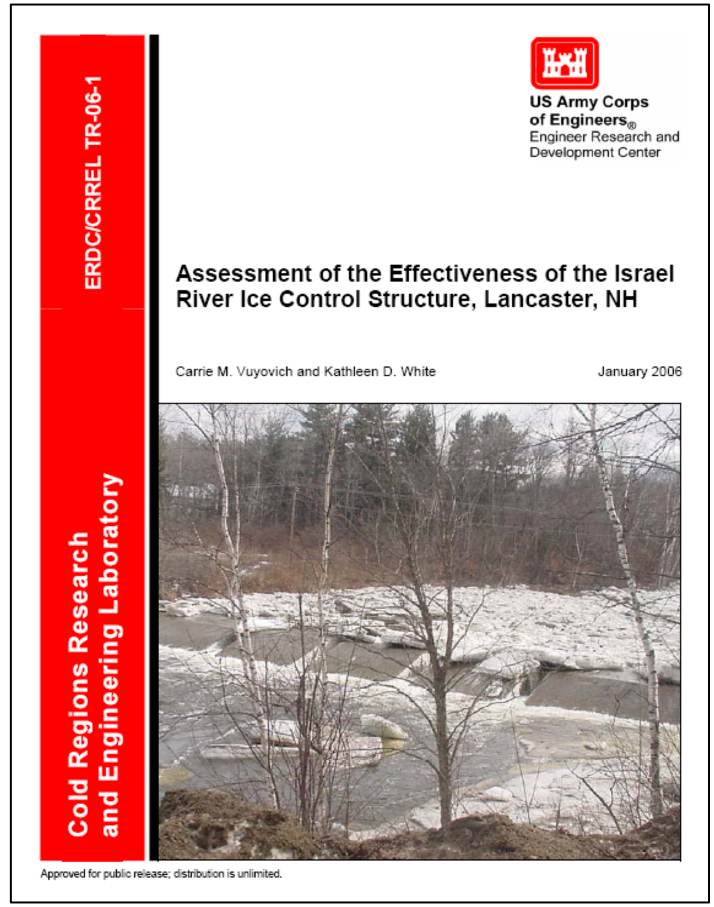
March 1992

Example of Analysis Method

- Compile meteorologic and hydrologic data for nearby locations in a database
- Perform extensive review of recorded ice events
- Evaluate meteorologic and hydrologic database to characterize the conditions in Lancaster at the time of an event
- Develop a set of threshold values or criteria which are likely to lead to the occurrence of a significant ice jam
  - Ice jams recorded prior to construction of the ICS were used to determine criteria likely to result in significant flooding due to a breakup ice event
    - Criteria were developed based on the five jams with the highest recorded stage (1968, 1950, 1970, 1973, and 1977)
    - The following severe breakup ice jam initiation criteria were established for the Israel River at Lancaster:
      - Ice thickness greater than 17 in. at the time of breakup;
      - Discharge of at least 1700 cfs more than the annual base flow at the time of the event;
      - Flow increasing at the time of breakup, but not for more than three days prior to breakup (i.e., rapid rise in discharge);
      - Temperatures that increased in the few days just prior to the jam but were not above freezing for an entire 10 days leading up to the jam (melt out); and
      - No ice breakup 30 days prior to the jam (i.e., no discharge > 1000 cfs).
- Apply criteria to post-ICS data to determine whether conditions likely to lead to a severe ice event occurred

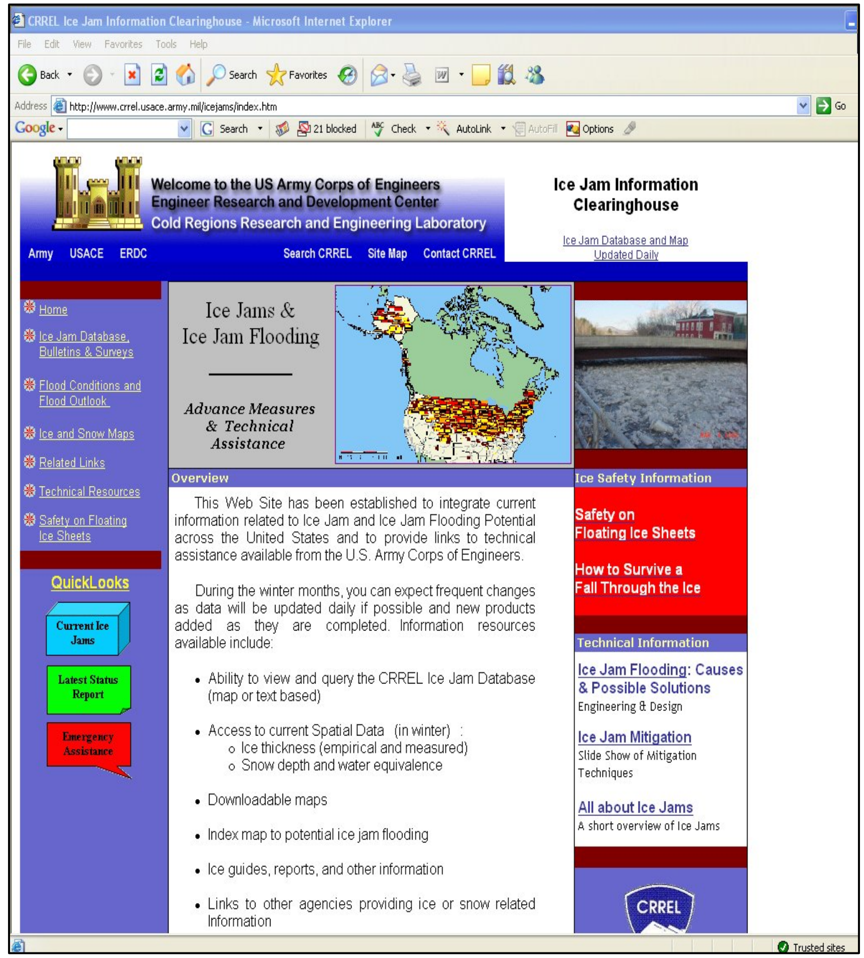
Results

- Criteria were applied to the data for the entire period of record to predict damaging ice jam floods
- Since construction of the ICS there have been no damaging ice jam events, so any predicted jams were assumed to be prevented by the ICS
- 14 significant ice jams were predicted for the period 1946 through 2004, including
  - five jams used to determine the criteria five known post-ICS jams
  - two of the identified may have occurred (1954 and 1959), a record search is required
  - 2002: an ice jam occurred on March 4, about a week before the predicted jam, but the ice was thought to be weaker and thinner than predicted by the Stefan equation due to a melt event recorded on February 12, 2002
  - 2004, a smaller jam was recorded by the monitoring equipment on March 27, 2004, about a week prior to the event predicted by the threshold criteria. The jam caused a stage increase of about 4 ft at the measuring site, and remained in place until 30 March, with a little shove on 29 March



Recommendations

1. Characterize existing ice regime
   - Ice formation, growth, breakup, transport, jamming
   - Upstream and downstream from dam
   - At least one winter of monitoring
   - Sources of information:
     - State dam safety office
     - USGS records
     - CRREL Ice Jam Clearinghouse
     - CRREL Ice Jam Database
     - Other historic documents (e.g., town histories)
2. Characterize ice regime prior to dam construction, if possible



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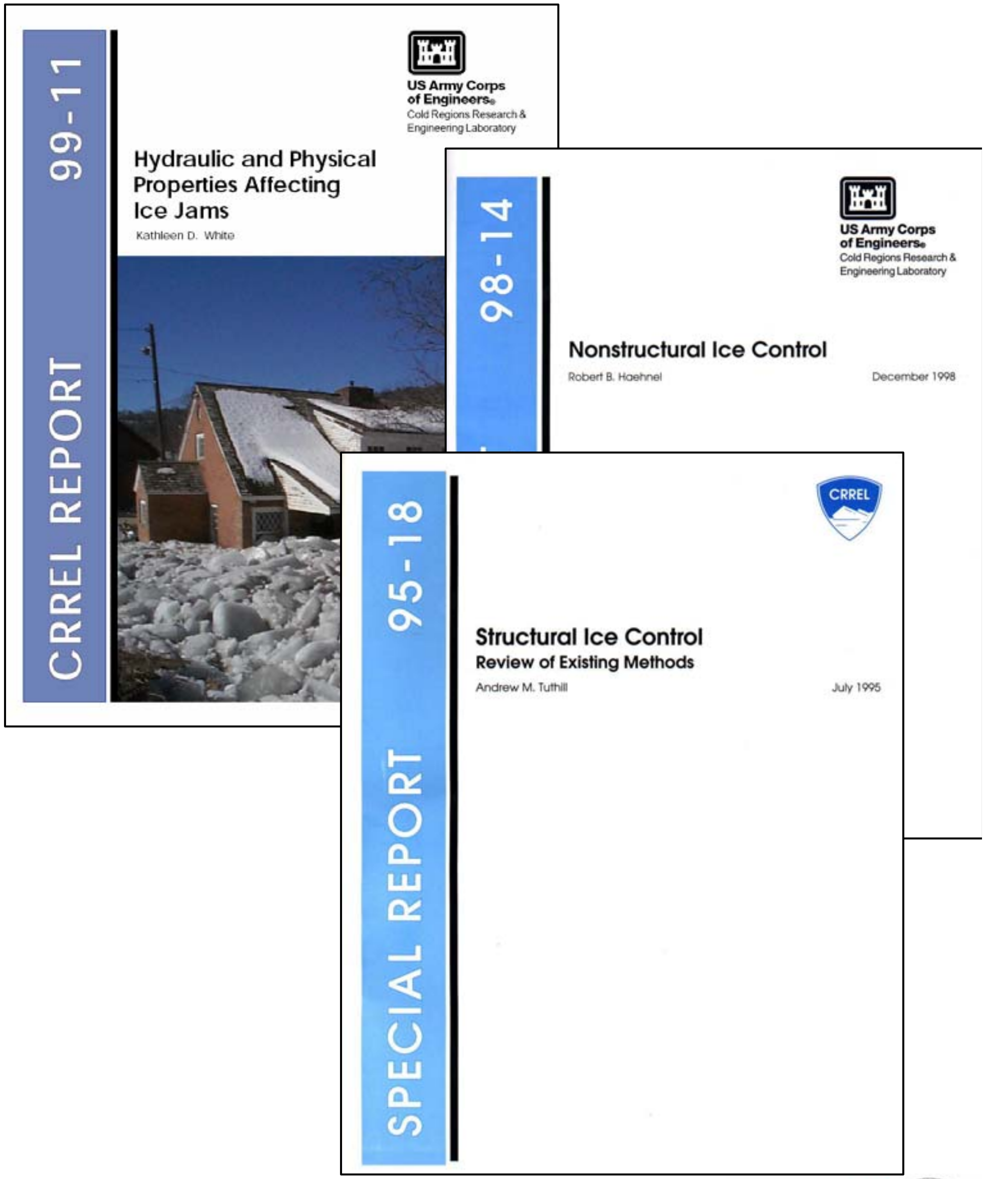
Recommendations

3. Perform hydraulic modeling of ice conditions if jams are known to occur near dam
   - Model with and without dam conditions to determine effects of removal on freezeup and breakup conditions
     - Frazil ice production and deposition
     - Estimate thermal ice thickness
     - Estimate breakup jam location and volume
     - Identify areas of ice-induced scour and erosion
     - Use HEC-RAS, UNET, multidimensional models (DynaRICE, DEM)
   - Consider ice mitigation measures if jam location changes or severity is predicted to increase
     - Numerous conference papers and technical reports available on ice control measures



Resources

- CRREL Ice Jam Database
  - http://www.crrel.usace.army.mil/ierd/ijdb/
  - Reported jam locations/pictures/reports/other
- CRREL Ice Jam Clearinghouse
  - http://www.crrel.usace.army.mil/icejams/index.htm
  - Rapid mapping of ice jam locations
  - Reaches Ice Jam Data Base text information
- Ice Engineering Information Exchange Bulletin
  - http://www.crrel.usace.army.mil/ierd/tectran/27InDesign.pdf
- Ice Engineering Manual
  - http://www.usace.army.mil/inet/usace-docs/eng-manuals /em1110-2-1612/toc.htm
- CRREL Technical Reports:
  - http://www.crrel.usace.army.mil/techpub/CRREL_Reports/ →River and Lake Ice
- ASCE J. Cold Regions Engineering
  - White, K.D. and J.N. Moore (2002) “Impacts of Dam Removal on Riverine Ice Regime.” *ASCE J. Cold Regions Engineering*, Vol. 16, No. 1, p. 2-16.
- Assessing the Effectiveness of the Israel River Ice Control Structure
  - http://www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/TR06-1.pdf

US Army Corps of Engineers®

Ice Engineering

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

Considerations for Dam Removal in Ice-Affected Rivers

During the past several hundred years, many dams have been built in the United States to meet the power, water supply, flood control, and recreational needs of a variety of users. The National Research Council estimates that there are about 2.5 million dams in the United States, ranging from small farm pond dams to large hydropower dams (NRC 1992).

Recently, increased awareness of the ecological, recreational, economic, and safety issues associated with dams has led to a reevaluation of the continuing existence of a number of dams. American Rivers et al. (1999) identified 467 dam removals in 43 states since 1912, with most removals in the latter part of that century (92 in the 1980s and 177 in the 1990s). Remediation or mitigation of ecological impacts are cited as the primary cause for many recent dam removals. Dam safety concerns and the costs associated with rehabilitation to meet dam safety criteria or environmental requirements also lead to dam removal (ASCE 1997).

Ecologically based dam removal often seeks to reestablish the pre-dam hydraulic regime of the river, which in turn can significantly affect the timing and peak values of flood hydrographs. As a result, typical dam removal studies (e.g., ASCE 1997) address open-water impacts of dam removals.

Another critical aspect of dam removal is the potential for adverse affects that can result from uncontrolled releases of sediment if dam removal is undertaken without an adequate sediment management plan. This is particularly important in impoundments known to contain contaminated sediments or fluvial tailings. ASCE (1997) provides a process for formulating sediment management plans associated with dam removal. USACE (1983) also addresses sediment management following dam removal under open-water conditions.

In northern rivers, dam removal and ensuing changes in hydraulic regime cause changes to the ice regime that may have significant local impacts on ice formation, ice cover growth and progression, ice cover breakup, and the movement and jamming of ice. In several cases, dam removal has resulted in increased frequency and severity of downstream jams (Fig. 1). Furthermore, lowering of water levels in impoundments containing sediment deposits may result in more frequent or longer duration ice-induced scour and erosion of bed and bank material. This is particularly important in impoundments where contaminated sediments have been deposited during the lifetime of the dam.

Ice-related adverse effects associated with dam removal can be miti-

Figure 1. March 1968 ice jam on the Israel River at Lancaster, New Hampshire. Ice jams increased in frequency and duration here following the failure or removal of four dams on the river between 1936 and 1950.

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